Universidade do Minho
Escola de Engenharia

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Sustainability Assessment of Envelope Wall Solutions Using MAXergy Methodology

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Integrated Research Project
International Master in Sustainable Built Environment

Supervisors
Professor Luis Braganca
Professor Ronald Rovers

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ABSTRACT

Since the 1987 Brundtland Report and 1992 United Nations Rio Declaration on Environment and Development, the ideals of sustainable development have been influencing the decisions made by designers and policymakers in the building industry. In the European Union building construction and operation currently represent about half of all extracted materials, one third of all waste generated, one third of all water consumed, and half of all energy consumed. This work proposes a justification for using regrowable biotic envelope wall building solutions to reduce these negative impacts and act as a more sustainable alternative to conventional wall solutions. A comparative Life Cycle Sustainability Assessment (LCSA) was conducted to evaluate the combined material-energy impact for adapted Netherlands straw, hemp/flax, and brick envelope wall elements within a theoretical closed loop system. The MAXergy methodology and Embodied Land Tool were used to provide a functional framework for the assessment by calculating a solution's embodied land for a wide range of thermal resistance states, which provided a physical and realistic unit to represent a closed system's resource capacity. The initial assessment resulted in the brick solution having an average of 17.9 times and 25.8 times more embodied land than the straw and hemp/flax solutions respectively. Depending on each solution's inputted material and PV panel rates of change, different optimum thermal resistance conditions were found. An additional analysis was conducted to determine a better understanding of the relationship between the material and PV panel impact on embodied land. The results provide a structure for recognizing aspects such as material density, thermal conductivity, climate zone and equipment coefficients of performance as significantly influential factors that shift the optimum embodied land conditions to a higher or lower thermal resistance value. With further development including more in-depth energy simulations and absolute material details, an ideal range of criteria could be determined and applied to a wide variety of building solutions in order to achieve optimal embodied land.

Key words: Life Cycle Sustainability Assessment, MAXergy, Embodied Land Tool, Sustainable Development, Biotic Materials

RESUMO

Desde o Relatório Brundtland de 1987 e da Declaração do Rio 1992 das Nações Unidas sobre Meio Ambiente e Desenvolvimento, os ideais de desenvolvimento sustentável têm influenciado as decisões tomadas por projetistas de edifícios e decisores políticos na indústria da construção. Na União Europeia a construção e operação de edifícios representam atualmente cerca de metade de todos os materiais extraídos, um terço de todos os resíduos gerados, um terço de toda a água consumida e metade de toda a energia consumida. Este trabalho propõe uma justificação para a utilização de soluções de construção de paredes-envelope bióticas regrowable para reduzir estes impactos negativos, apresentando-se como uma alternativa mais sustentável às soluções de paredes convencionais. Foi realizado neste trabalho um estudo comparativo da Avaliação de Sustentabilidade do Ciclo de Vida (LCSA - Life Cycle Sustainability Assessment) para avaliar o impacto combinado de material e energia em blocos de fachada teoricamente executados em palha Holandesa adaptada, cânhamo/linho e paredes exteriores em tijolo, num sistema teórico de circuito fechado (closed loop system). A metodologia MAXergy e Embodied Land Tool foram usadas para fornecer um quadro funcional para a avaliação calculando a terra incorporada de uma solução para uma ampla gama de estados de resistência térmica, o que forneceu uma unidade física e realista para representar a capacidade de recursos do sistema fechado. A avaliação inicial resultou numa solução de bloco com uma média de 17,9 vezes e 25,8 vezes mais terra incorporada do que as soluções de palha e de cânhamo/linho, respetivamente. Dependendo do material imputado a cada uma das soluções e das taxas de mudança dos painéis FV, foram encontradas condições para diferentes resistências térmicas ótimas. Uma análise adicional foi realizada para determinar a melhor compreensão da relação entre o material e o impacto do painel fotovoltaico na terra incorporada. Os resultados fornecem uma estrutura para o reconhecimento de aspetos como a densidade do material, condutividade térmica, zona climática e coeficientes de desempenho de equipamentos como fatores significativamente influentes que mudam as condições ótimas de terra incorporada para um valor maior ou menor de resistência térmica. Com um maior desenvolvimento, incluindo simulações mais aprofundadas da energia e de detalhe do material total poderia ser determinada uma faixa de critérios ideais a serem aplicados a uma grande variedade de soluções de construção a fim de alcançar o nível ótimo de terra incorporada.

Palavras-chave: Avaliação da Sustentabilidade do Ciclo de Vida, MAXergy, Embodied Land Tool, Desenvolvimento Sustentável, Materiais bióticos

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LIST OF ABBREVIATIONS

BIM: Building Information Modeling

CEN: European Committee for Standardization

CIB: International Council for Research and Innovation in Building and Construction

EFTA: European Free Trade Association

EL: Embodied Land

EPA: United States Environmental Protection Agency

EPBD: Energy Performance of Buildings Directive

EPC: Energy Performance Calculation

EPD: Environmental Product Declaration

IEA: International Energy Agency

ISO: International Standards Organization

IUCN: International Union for Conservation of Nature

LCA: Environmental Life Cycle Assessment

LCC: Life Cycle Costing Assessment

LCI: Life Cycle Inventory

LCIA: Life Cycle Impact Assessment

LCSA: Life Cycle Sustainability Assessment

MDGs: Millennium Development Goals

PCR: Product Category Rules

RiBuilT: Research Institute Built Environment of Tomorrow

SETAC: Society of Environmental Toxicology and Chemistry

SDGs: Sustainable Development Goals

SLCA: Societal Life Cycle Assessment

UNDP: United Nations Development Program

WWF: World Wide Fund For Nature

WorldGBC: World Green Building Council

1 INTRODUCTION

What will the homes, buildings, and cities of far future generations look like? Will they be made from advanced composite materials and technology that enhance the designs durability and efficiency? Or will they be made from the less processed biotic regrowable materials that were commonly being used during humanity's early history? These are questions that anybody invested in the sustainability of the building industry and humanity should be contemplating. Many governments and organizations from all over the world have been devoting more time, investing more resources, and collaborating internationally on ensuring humanity will be able to ideally sustain itself indefinitely. With influence from national and local governments, many resource intensive industries like the building industry now have to focus on adopting the ideals of sustainable development.

The mindset that environmental impacts can significantly affect humanity has always existed within the ideals of preservationists, conservationists, and environmentalists throughout history. But it was not until the 1960s that these scientific groups were able to gain sufficient support from the general public and world leaders by calling attention to these environmental impacts in several publications. The book "Silent Spring" by Rachel Carson came out in 1962 and showed direct connections between the accumulation of agricultural pesticides and damage to animal and human health (Carson, 1962). In 1968 Paul Ehrlich published the book "Population Bomb" and discussed the relationship between the human population, resource exploitation, and environmental limitations (Ehrlich, 1968). During this time and up until the late 1980s many major organizations were established, conferences were held, and initiatives were started to address the growing concerns about environmental integrity, human health, and sustainable development.

The idea of sustainable development was first officially defined in the 1987 Brundtland Report, "Our Common Future" (Brundtland, 1987). The United Nations (UN) later adopted the objective of creating a more sustainable world during the Earth Summit of 1992 in Rio de Janeiro. This summit produced the voluntary action plan, Agenda 21, which defined a broad foundation for creating solutions to sustainable development problems by connecting social, economic, and environmental issues (UN, 1992). Soon after in 1999, the internationally accepted study, Our Common Journey: A Transition Toward Sustainability, provided an in-depth look at how the trends of rapid population growth, increasing consumerism, and living outside resource limits during 1999 could negatively affect future generations (NRC, 1999). This study also brought global attention to the many unanswered questions involved with finding sustainable solutions and the need to develop a sustainable science discipline. These early concepts of sustainable development began as broad relative definitions and goals, but inspired the more detailed plans, calls to action, and research that followed.

Sustaining humanity's way of life is a complex concept when considering it revolves around many different segregated professions trying to solve a vast amount of known and unknown problems. Problems that are interconnected and if not solved correctly they can repeatedly facilitate each other in a cycle. For example, a product that is designed to help reduce the consumption of fossil fuels actually may require consuming a higher amount of fossil fuels for its own production, transportation, operation, disposal, or recycling. The same product also may have its potential hindered by certain governmental policies and economic limitations, which as a result allows the targeted issue to continue to exist, defeats the purpose of designing the product in the first place, and contributes to waste. It is easy to see how trying to develop one sustainable solution can quickly become complicated and overwhelmed with many different factors.

These sustainability problems are not only physical but also psychological. Whether it is for transportation, power generation, agriculture, industries, commercial businesses, or residential homes, the effectiveness of sustainable solutions is directly dependent on human behavior. If the majority of a society does not understand how to or deliberately chooses not to use sustainable products as they were intended, then this is an issue that needs to be addressed through enforcing policies, education, and intuitive designs. Even then, any psychological factor affecting a design is qualitative and a sensitive issue to implement with quantitative figures.

In terms of affecting physical and psychological sustainability solutions, built environments will have a significant influence in the near future. In the European Union building construction and operation currently represent about half of all extracted materials, one third of all waste generated, one third of all water consumed, and half of all energy consumed (EC, 2014 a). Most populations thrive in and depend on built environments. If sustainable solutions are increasingly implemented into the design of buildings then by proximity, operation, and association societies gradually will become accustomed to these sustainable products and others like it.

This paper will consider two main building design strategies in order to gain a better understanding of how best to create a sustainable building solution and in turn a more sustainable society. The current mindset on sustainable solutions within most construction industries is to view the potential improvements for contemporary building solutions as the best way to achieve sustainable development goals. Since the industrial revolution during the 19th century, economically cheap and mostly non-regrowable materials have been increasingly extracted and used for most of the contemporary building solutions today. Depending on the regional location, these materials include steel, aluminium, brick, stone, and concrete to name a few. To show

how dependent construction industries have become on these materials, concrete is actually the second most used material in world next to water (WBCSD, 2014).

These contemporary building solutions and materials that societies have grown accustomed to have helped humanity achieve a higher quality of life over the past few decades. Built environments have been constructed with a wide variety of functional performances and they excel at pushing the limits of structure size. With improvements to manufacturing, production, and recycling processes, the construction industry has been able to achieve lower costs, reduced energy losses, faster project completions, and less negative environmental impacts. But there are still significant limitations to these improvements that need to be addressed.

The more processed, composite, synthetic, and complex these contemporary solutions become the more energy, resources, skill, and training is needed to maintain their higher quality. In addition it becomes increasingly more difficult to repurpose and appropriately dispose of these solutions in order to optimize their usefulness within a life cycle.

Since modernization has led to more dependency on faster and cheaper construction, in many cases these solutions result in less efficient structures. In order to compensate for this, most modern building solutions heavily rely on mechanical heating and cooling equipment to optimize the building performance, which is currently responsible for more than one-third of global energy consumption (IEA, 2013).

After considering these limitations it can be said that maybe the current trend of trying to enhance contemporary solutions is not the only way to achieve a more sustainable built environment and maybe not even the best way to attempt to create an ideal built environment that can sustain itself indefinitely. It is known that in humanity's past there were more structures made from materials that could be easily harvested and regrow with low energy processes. So the question arises, why has the investment in developing regrowable biotic building solutions not been more seriously considered in the mainstream construction industry?

Since there is not an official consensus on some material labels it is important to clarify them to ensure a transparent discussion on this sustainability assessment of materials. Realistically all materials come from nature and all materials can be regenerated in some way, thus calling some materials natural, organic, man-made and renewable while excluding others is arbitrary and inaccurate. The following material labels defined below will be used to show certain logical distinctions between material groups throughout this paper:

- Biotic or bio-based materials: any material originating from living organisms, typically with little to no processing, usually containing carbon and capable of decay such as wood, straw, hemp, and bamboo.
- Regrowable materials: any material that can regrow itself with a natural reproduction mechanism within a generation's lifetime.

Traditional, biotic material building methods are still used in many parts of the world and are starting to gain more popularity today. These methods are minimalistic and passive in design and mostly take advantage of local regrowable materials to maximize comfort within the regional climate. By focusing on this perspective of sustainable design and using traditional approaches almost all dependency on heating and cooling can be eliminated, except for extreme climates. This strategy is currently being called for by IEA-UNDP (2013).

The biotic and regrowable building materials that have shown a lot of potential for becoming viable substitutes for contemporary materials are: adobe brick, cob, wood, hemp, bamboo and straw-bale. Adobe brick and cob are comprised of a combination of sand, clay, water, and some form of fibrous organic material. Straw, hemp, bamboo and wood can all be used in almost pure form within building solutions and have a relatively small production process. But harvesting wood requires a long growing process and risks the negative environmental impacts of deforestation and reducing biodiversity. Bamboo is one of the fastest growing plants in the world, known to be capable of being stronger than wood, and can be grown in diverse climates. On the other hand, straw-bale and hemp are mass-produced agricultural byproducts that are typically wasted or converted into energy very early in their life cycle.

Unfortunately with the rise of dependency on the industrial age building solutions, there was also the loss of traditional building practices. The use of regrowable and biotic materials in the construction industry is currently limited to small private businesses, volunteer workshops, and not-for-profit organizations. The main factors impeding the recognition and justification of these alternative solutions are a lack of experience, knowledge, and skill from building designers, contractors and policymakers. This has led to both psychological hesitations and legislative gaps.

Psychologically, regrowable biotic materials tend to be associated with low-quality structures and a lower quality of life in undeveloped countries with poorer economies, which is an opinion that can be disproven logically. Initially it can be said that the definition of quality of life is subjective and inaccurate to assume in relation to a structure. But for the sake of continuing the argument in this case, quality of life will be associated with income, average health conditions, and the ability to pursue happiness. Just by using this broad definition it can easily be seen that there are many documented cases of local populations in undeveloped countries having a lower quality of life and suffering while living within traditional regrowable and biotic built environments. But there are also many cases of the exact opposite scenario, where regrowable biotic buildings have been designed and built within developed countries and considered to provide a high-quality life. Since both of these two scenarios exist, it can be concluded that the building materials themselves do not solely dictate the social status, economic status, and quality of life of the building occupants. Therefore the negative psychological stigmas associated with regrowable biotic building materials cannot be objectively justified and have the potential to be reduced over time if the general population becomes more accustomed to these solutions as they are implemented more into the mainstream construction industry.

Legislatively there are relatively few policies that support these alternative regrowable biotic building solutions by local and national governments when compared to the well-established conventional building solutions. But with the sustainable development goals of the 21st century, some opportunities are currently being developed by international government bodies to facilitate identification and labelling systems for sustainable products. Environmental Product Declarations (EPDs) have been developed in both the European Union and United States as a way to label the environmental impacts of a product's life cycle. This label requires the use of current life cycle assessment tools and methodologies as well as the development of Product Category Rules (PCRs). These rules define how products will be evaluated and are a consensus of all actors participating in developing the EPD. Although EPDs are currently focused on only the environmental impacts, they can easily be adapted to include a complete analysis of sustainability impacts over a life cycle. But there are some limitations to EPDs and their PCRs. There is a lack of standardized terminology, methods to define system boundaries, and assuring the quality of data to support the credibility of EPDs (Schenck and Lalonde, 2013). Therefore while EPDs and PCRs will require future improvements from policymakers, building companies and researchers can continue to rely on optimized assessments of product life cycles.

1.1 Objectives

The goal of this paper is to show how building designs that use regrowable biotic materials are more sustainable than contemporary building designs that use more complex and highly processed materials. A comparison analysis was conducted using the sustainability life cycle assessment methodology called MAXergy, which focuses on quantifying a product's material and energy burden within a closed system. This analysis shows how far away a product is from an ideal sustainable solution and explores the relationship between the material and energy impact on a solution's embodied land.

This paper's research was done in cooperation with the EU Horizon 2020 Project called More-Connect (*Development and Advanced Prefabrication of Innovative, Multifunctional Building Envelope Elements for Modular Retrofitting and Smart Connections*, 2014). The goal of More-Connect is to facilitate progress towards near 0-energy in existing buildings by developing methodology and technical solutions for mass renovation. There are currently 7 different countries from five different climate regions participating in More-Connect. The results from this paper's sustainability assessment will help set guidelines for the design of modular prefab renovation wall panels for different housing typologies.

Current European goals, standards and recent case study examples of life cycle assessment were reviewed in the next section of this paper in order to gain more context on the objectives that relate to the sustainability assessment of this paper and the goals of the More-Connect Project. Additionally, previous MAXergy development and research were reviewed to provide direction for the focus of this paper's analysis.

2 STATE-OF-THE-ART

2.1 Review of Current Definitions, Terminology, and Standards Associated with Sustainability Life Cycle Assessment

The original definition of life cycle assessment (LCA) for a product was commonly associated only with evaluating environmental impacts. Since the proposed sustainability definition in the Brundtland Report (1987), the discussions from the SETAC Europe LCA Symposium in 1991, and the UN Rio Declaration on Environment and Development in 1992 (UN, 1992), there has been a global consensus that a full life cycle sustainability assessment (LCSA) should include social and economic impacts as well as environmental. Although there are a few different variations for labelling these assessments, the recent "Life Cycle Sustainability Assessment of Products" by Kloepffer gave a simple summary of the different terms (2008). The economic dimension is referred to as a life cycle cost assessment (LCC) and the social dimension is referred to as a societal life cycle assessment (SLCA). **Equation 2.1** represents the current agreed upon composition of an LCSA:

$$\text{LCSA} = \text{LCA} + \text{LCC} + \text{SLCA} \tag{2.1}$$

LCSA = Sustainable Life Cycle Assessment

LCA = Environmental Life Cycle Assessment

LCC = Life Cycle Costing Assessment

SLCA = Societal Life Cycle Assessment

Since the development of LCSA is still in its infancy, there is a small amount of standardization on LCSA as a whole concept. **Table 2.1** summarizes the current main standards on LCSA that apply to building solutions internationally and in the EU.

Table 2.1: Key International Standards on Life Cycle Sustainability Assessment.

ISO 15392	2008	Sustainability in building construction – General Principles
ISO 21929 Part 1	2011	Sustainability in building construction – Sustainability Indicators
UNEP & SETAC Life Cycle Initiative	2011	Towards a Life Cycle Sustainability Assessment: Making informed choices on products

The majority of these standards are general in nature and only provide principles or frameworks for LCSA methodology. This is because sustainability is a complex combination of systems, processes, and unknown external factors, which makes it impossible to define one set of evaluation methodologies for the whole world. Instead these standards are intended to find a balance between being adapted to an assessment practitioner's needs for specific regional locations and not losing the fundamental requirements that have already been established.

2.1.1 Environmental Life Cycle Assessment

An environmental LCA is comprised of four key stages that have been well established and recognized as the main reference for any other type of LCA. These four stages can be defined as the following:

- Stage 1: Definition of system scope and boundaries being evaluated
- Stage 2: Life cycle inventory analysis
- Stage 3: Life cycle impact assessment
- Stage 4: Interpretation of Results

Only environmental LCA methodologies have well-established international standards. ISO has been developing the 14040 environmental management standards relating to LCA since 1993 with the help of standards bodies from 162 member countries. The first ISO 14040 standard for LCA was originally based on the Code of Practice developed by SETAC (Lecouls, 1999). Since then ISO has revised the 14040 standard guidelines three more times with versions 14041, 14042, and 14043. In 2006 these past standard revisions were combined into a new 14040 standard labeled ISO 2006a and an additional 14044 standard was published with more detailed requirements labeled ISO 2006b. **Appendix Figure A.1** shows a complete list of definitions and degree of changes made between the old 14040 and new 14040 standards. These revisions addressed many fundamental issues, such as (Pryshlakivskya and Searcy, 2013):

- Providing more clarity by revising terminology and definitions
- Including previously absent guidelines on uncertainty, weighting, and allocation
- Allowing more flexibility on modifying system boundaries

Today many LCAs being developed around the world are significantly influenced by the ISO standards, but assessment practitioners mostly use these standards as a supplement for more optimized guidelines (Cooper and Fava, 2006).

2.1.2 Life Cycle Cost Assessment

LCC has been used in the construction industry a lot longer than LCA, but it has required almost no scientific standardization since the analysis of monetary aspects is easily understood and already well-established within the economic systems used by most societies. There are many different forms of LCC but in terms of applying it to an LCSA, there is only one suitable method. The foundation of an LCSA is based on the environmental LCA methodology due to how complex it is to quantify and how much influence it has on the final accuracy level of results. In order for the LCC to achieve the same accuracy level and be consistent with the quality of the LCA it must follow as close to the same methodology as possible. An environmental-based LCC quantifies all real money flow costs associated with similar system boundaries and unit processes as the environmental LCI. Unlike LCA, there is no impact assessment for LCC due to the final results being a calculated cost per functional unit. It would be too difficult to estimate future costs associated with environmental impacts and impossible to consider them as real money flows.

2.1.3 Societal Life Cycle Assessment

SLCA is not a new idea, but also like LCC it lacks standardization except for specialized cases. There can be many overlapping societal factors with LCC and LCA. Also it is very difficult to quantify many societal factors at once, which means qualitative rankings have a higher chance of being used. This can lead to subjective weighting and ultimately a possible risk of unreliable results for comparison and a lack of justification. In order to reduce these risks only quantifiable, non-overlapping societal factors should be considered for the LCSA and they should be related to the same system boundaries and unit functions as the LCA.

2.2 Review of Current Goals and Standards That Apply to Sustainable Building Assessment in the Netherlands

With the established Agenda 21 goals from the 1992 UN Conference on Environment and Development held in Rio de Janeiro, Brazil, an international conversation was started on sustainable development. This conversation has kept going ever since and improvements have continued to be made to the concept of balancing environmental, economic, and societal aspects of humanity in order to achieve a more sustainable life style.

In 2000 during the UN Millennium Summit in New York, U.S., the world leaders adopted the United Nations Millennium Declaration and defined the new Millennium Development Goals (MDGs) with a deadline of 2015 (UN, 2014 a). Then again in 2012 at the most recent UN Conference on Sustainable Development in Rio de

Janeiro, the same principles were built upon and renamed the Sustainable Development Goals (SDGs). These most recent targets will see the convergence of the pre-2015 and post-2015 plan and guide the world to the new deadline of 2030 (UN, 2014 b).

In relation to built environments and sustainable design, the Agenda 21, MDGs, and SDGs do not define any detailed requirements and instead consist of many broad reaching sustainability objectives that cover topics such as poverty, hunger, health, and accessibility. But a couple SDGs, which are shown below in **Table 2.2**, do provide a few general goals that are directed towards built environment design and therefore are relevant.

The SDGs described above in **Table 2.2** are still very broad and meant to be applied as guidelines for large scale concepts universally around the world.

In 2003 the World Wide Fund For Nature (WWF) organization provided ten "One Planet Living" principles that outlined broad sustainable goals similar to the SDGs. Conceived in 1961, WWF is currently one of the largest conservation organizations in the world and is dedicated to stopping the degradation of the planet's natural environment by focusing on assessing biodiversity and ecological footprints. WWF has offices in over 80 countries and cooperates with many partners including UN organizations, International Union for Conservation of Nature (IUCN), USAID, and the World Bank.

The WWF goals pertaining to building design include the following (WWF, 2003):

- Achieve net zero CO2 emissions by implementing energy efficiency in buildings and infrastructure; supply energy from on-site renewable sources, topped up by new off-site renewable supply where necessary.
- Eliminate waste through more efficient designs that use recycling and composting; generate energy from waste, and create a resource efficient society.
- Use local, reclaimed, renewable, and recycled materials in construction and products; this minimizes transport emissions, increases investment in local resource stocks and benefits the local economy.
- Implement water use efficiency; minimise water extraction and pollution; sustain water and sewage management; restore natural water cycles.

On a slightly more focused scale, The International Council for Research and Innovation in Building and Construction (CIB) has participated in research and development relating to the topic of integrated design and delivery solutions specifically for the construction industry as a whole. Although integrated design and delivery is not the same phase as assessment, it shares many of the same values and can significantly impact the final sustainability grade of a building.

Table 2.2 SDGs directed at built environment design (UN, 2014 b)

Goal 9: Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation.	Goal 11: Make cities and human settlements inclusive, safe, resilient and sustainable.
9.1 – Develop quality, reliable, sustainable and resilient infrastructure, including regional and trans-border infrastructure, to support economic development and human well-being, with a focus on affordable and equitable access for all. 9.4 – By 2030 upgrade infrastructure and retrofit industries to make them sustainable, with increased resource use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes, all countries taking action in accordance with their respective capabilities.	11.3 – By 2030 enhance inclusive and sustainable urbanization and capacities for participatory, integrated and sustainable human settlement planning and management in all countries. 11.6 – By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality, municipal and other waste management. 11.a – Support positive economic, social and environmental links between urban, peri-urban and rural areas by strengthening national and regional development planning. 11.b – By 2020, increase by x% the number of cities and human settlements adopting and implementing integrated policies and plans towards inclusion, resource efficiency, mitigation and adaptation to climate change, resilience to disasters, develop and implement in line with the forthcoming Hyogo Framework holistic disaster risk management at all levels.

Established in 1953, CIB is now an international network of over 5,000 building and construction experts from about 500 active member organizations in the research community, industry, or education. CIB has released a recent research roadmap detailing their proposed solutions for sustainable development within building design teams. To summarize the goals of integrated design and delivery strategies, it is possible to achieve more efficient work, faster project completions, less waste-related costs, and improved project reliability and quality. The research roadmap showed these benefits as the result of implementing the following (Owen et al., 2013): Interoperable technologies such as Building Information Modelling (BIM); Integrated Processes including Lean Construction; Collaborating People.

In 2008 the EU Commission adopted a new proposal for the Energy Performance of Buildings Directive (EPBD) and supported the approval process. On May 19, 2010, the EPBD recast was adopted by EU Parliament and the Council of the European Union to replace the 2002 Directive. This proposal confirms the importance of effective implementation of Member state level, community-wide cooperation, and strong long-term commitment of support from the Commission. The end goal is to have the EU consume 11% less final energy via the reduction of building energy consumption. The major highlights of the EPBD recast relating to building design are as follows (ECEEE, 2010):

- As of December, 31, 2020 new buildings in the EU will have to consume 'nearly zero' energy and the energy will be from renewable sources.
- The definition of very low energy building was agreed to: "nearly zero energy building means a building that has a very high energy performance, determined in accordance with Annex I. The nearly zero or very low amount of energy required should to a very significant level be covered by energy from renewable sources, including renewable energy produced on-site or nearby."
- There is no specific target to be set for the renovation of existing buildings, but Member States shall following the leading example of the public sector by developing policies and take measures such as targets in order to stimulate the transformation of buildings that are refurbished into very low energy buildings, and inform the Commission thereof in their national plans.
- MS will be required to introduce penalties for non-compliance. Member States shall lay down the rules on penalties applicable to infringements of the national provisions adopted pursuant to this Directive and shall take all measures necessary to ensure that they are implemented. The penalties provided for must be effective, proportionate and dissuasive. Member States shall communicate those provisions to the Commission.

In 2010 the European Commission additionally launched a sustainable development strategy, which set the following climate change and energy sustainability targets for the year 2020 (EC, 2014 b):

- Lower greenhouse gas emissions 20% from 1990 levels
- Obtain 20% of total energy from renewable sources
- Increase energy efficiency 20%

Table 2.3 IEA Technical Roadmaps for Energy Efficiency (IEA, 2011)

Energy-efficient Building Envelopes Roadmap Summary.	Energy-efficient Building Heating and Cooling Equipment Roadmap Summary.

• Design envelopes that use energy-efficient materials and passive strategies to heat and cool.
• Deep renovation or reducing energy consumption as much as possible when renovating existing building stock.
• Air-sealing and testing for air leakage regularly.
• New work buildings should optimize daylighting by using integrated facades that additionally reduce energy requirements.
• Globally collaborate to develop zero-energy buildings.
• Research and Design the following technologies:
    o High insulated windows.
    o Advanced, high, performance, “thin” insulation.
    o Less labor-intensive air sealing, and lower-cost validation.
    o Lower-cost dynamic shading and glazing.
    o More durable and lower-cost reflective roof materials and coatings.
	• New technology such as solar thermal, combined heat and power, heat pumps, energy storage, and bioenergy potentially can save 710 million tons oil equivalent of energy by 2050.
	• By 2030 R&D needs about USD $3.5 billion a year to focus on reducing costs and improving efficiency of equipment components.
	• Beyond 2030 R&D should focus on developing technologies that go beyond the best of what is currently available.
	• Policies need to be general enough to address certain barriers and deep enough to be applicable to all fragmented stakeholders within the building sector.

The European Committee for Standardization (CEN) has created Technical Committee (TC) 350 to develop voluntary standards on sustainable assessment methodologies. CEN has been officially recognized by the European Union and the European Free Trade Association (EFTA). In 2005, TC 350 began work on integrated performance assessment methodology standards over a building’s life cycle that combined the environmental, life cycle cost, and quantifiable health and comfort performance aspects. While the assessment of social performance of buildings is still under development, the assessment of environmental performance was described under the CEN/ TC 350 standard of EN 15978 in 2011 as following the same methodology of LCA and Environmental Product Declarations (CEN, 2005).

The International Energy Agency (IEA) has been closely monitoring building energy consumption over the past decade. Founded in response to the 1973 oil crisis, the IEA is an organization that works to ensure its 29 member countries have reliable, affordable and clean energy. It is a significant actor in the global conversation on energy, providing authoritative statistics, analysis and recommendations. In the past few years the IEA has released numerous technological roadmaps outlining energy efficiency improvements for buildings. The key roadmaps relating to the topic of this paper are summarized in **Table 2.3** (IEA, 2011).

The IEA also assesses its member countries every few years and updates their energy policies. There is currently a 2014 Review for the Netherlands, which discusses the current state of the country's energy production and demand. Since the last review in 2008, the Netherlands has become Europe's second-largest producer of natural gas and has invested greatly in oil and gas storage; coal, oil and gas terminals; and more efficient power plants. These investments have provided more energy stability, but natural gas production has started to decline and according to IEA, should be further developed in order to make it through this transition period. Because the Netherlands is currently one of the most fossil-fuel and CO2 dependent IEA member countries, an Energy Agreement has been established to support key actions through 2020 that will increase the country's reliance on renewable energy sources (IEA, 2014 b).

These goals are specific to the Netherlands, but they are still similar to the international objectives and common perspective on sustainable development mentioned above.

The Netherlands government additionally plans on improving its environmental, economic, and social sustainability performance in the next five to ten years. The Netherland Issue Policies (2014) that should be considered for the MAXergy building project include the following:

- Implementing energy labels for every home starting in 2015. This label will show how energy efficient the buildings are while encourage people to invest more in energy-saving actions at the same time.
- A €600 million budget financed by the National Energy Saving Fund that homeowners can use to invest in energy-saving measures and tax breaks for people who generate electricity from sustainable resources.
- Conservation of nature and biodiversity.

- Ensuring sufficient resources for a world population of nine billion in 2050, with a sustainable consumption and production action plan.

A perspective that is similar and a source of inspiration for the MAXergy methodology used in this paper is defined by the organization, The Natural Step (TNS). TNS is a global network with 25 years of experience in developing strategic sustainable development and providing its partners from 13 countries with education and recommendations. The mission of TNS is to enable people to use its sustainability principles to ensure human society can survive within nature's limits (TNS, 2013).

TNS defines the main cause of sustainability problems lies with the systematic increase of negative human impacts, not the impacts themselves. As long as the impacts were small enough and consistent, the Earth's tolerances would be able to compensate for them. This approach has been based on the following scientific laws of nature that can be observed (TNS, 2013):

- Solar energy is the source of almost all material quality increase and can easily be seen in photosynthesis. It is the flow of sunlight that continuously creates order and structure from the constant increase in disorder within the isolated system of Earth. This is supported by the Second Law of Thermodynamics.
- The value of materials is not in how much energy or matter it contains but rather in the structure, concentration, and performance ability of that energy. This is due to the First Law of Thermodynamics and the Law of Mass Conservation that states energy and matter of an isolated system cannot be created nor destroyed.
- Because nothing truly disappears, when matter is burned it is not destroyed but turned into waste.
- Also because of the Second Law of Thermodynamics (Entropy), both energy and matter tend to disperse and dissipate as they travel through a system. This means that the amount of useful energy continues to decrease each time it is transformed.

In addition TNS encourages a backcasting approach to developing sustainable solutions and strategies. Backcasting is the concept of creating a plan and solution by defining the end result first, then the current situation, and finally working backwards to achieving the final result (TNS, 2013).

2.3 Review of Recent Relevant LCA Examples

Although building with traditional straw-bale solutions has been gaining popularity in the world, there are not many published studies of fully developed LCSA on this specific material. Since there is a lack of experience building with straw-bale in the construction industry and there is not much existing data to complete a full LCSA, most studies are only focused on building an environmental LCI in order to justify its use.

Table 2.4 60-year LCIA results of different wall solutions for UK LCI case study (Sodagara et al., 2011).

	Without sequestration:		With sequestration:	
Construction:	Total kg CO^2	kg CO^2/m^2 floor area	Total kg CO^2	kg CO^2/m^2 floor area
Straw-bale	51761	603.6	31739	370.1
Engineering timber frame	53022	618.3	38493	448.9
Brick-clad timber frame	54904	640.3	39040	455.3
Rendered masonry	55069	642.2	41163	480
Brick-faced masonry	58411	681.2	44506	519

The following two journal article summaries are recent examples of how an environmental LCI of straw-bale wall solutions can be created:

1. (González, 2013): An environmental LCI quantifying embodied energy and GHG emissions for straw-bale envelope wall solutions was conducted using scope boundaries local to Andean Patagonia. Only the manufacturing, production, transportation to construction site, and construction phases were considered from the life cycle. The main sources of input data were obtained from local producers, manufacturers, and construction companies. The results were compared to an LCI for conventional, local wall solutions. The straw wall solutions were shown to have a lower embodied energy and GHG emissions per m^2. They also had better thermal performance.
2. (Sodagara et al., 2011): An environmental LCI quantifying embodied CO_2 emissions for straw-bale social housing buildings was conducted using scope boundaries local to the United Kingdom. All life cycle stages were considered and the main input data sources were obtained from national averages or literature review from similar case studies. The LCI results were compared to conventional, local building solutions and showed how perspective on the best solution changes depending on the inclusion of sequestration of CO_2.

Both of these examples demonstrate the first two stages of an LCA methodology, but they use different boundaries and evaluate slightly different inputs. Due to subjective assumptions and the use of data sources outside their system boundaries, the accuracy of some of their results suffered and was not well-justified. As previously discussed, these example LCI methodologies show the importance of the first stage of LCA and how it applies to all aspects of LCSA. **Table 2.4** illustrates this point by showing how the final CO_2 emission result from the UK LCI example change depending on the consideration of sequestration or not.

2.4 Review of RiBuilT's District of Tomorrow Research in the Netherlands

The MAXergy methodology used for this paper's sustainability assessment was developed for a 100% bio-based building student-designed project. This project was among three others as a part of a District of Tomorrow concept that was created at the Zuyd University by the Research Institute Built Environment of Tomorrow (RiBuilT) in late 2010 in order to try and provide a practical platform for stakeholders, education, and local government to use as a transition tool for a more innovative sustainable region. With the cooperation of fellow pupils and partnered professionals, the final student designs are constructed and innovative industry strategies are researched (SBSC, 2014).

The 100% bio-based building is still being researched and designed to reach its original goal of becoming one of the first modern buildings in the world to be able to produce or compensate all of its resources on site. According to the MAXergy Methodology and Embodied Land Calculation Tool, in order to be able to regrow the same building within a life span of 50 years on site efficiently, 100% of the materials should be regrowable, bio-based and low energy cost renewable (SBSC, 2014).

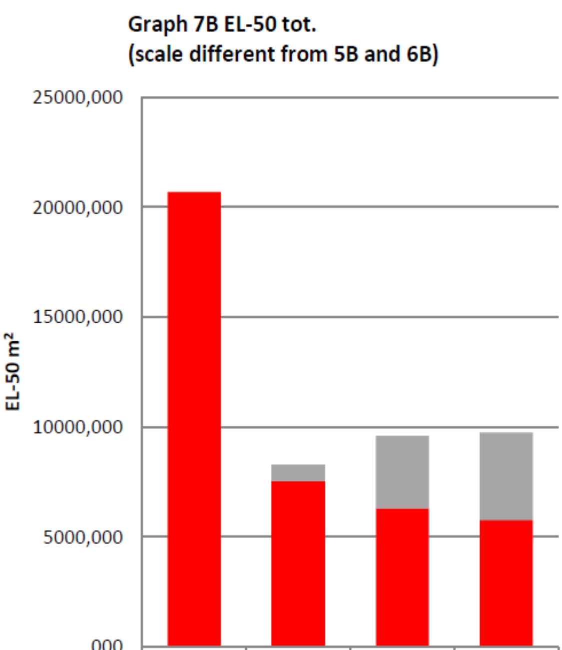
The chosen student design has been able to achieve an 82% by weight bio-based solution. Mostly indoor finishing materials and the photovoltaic solar panels chosen to provide energy remain to be converted to bio-based alternatives. The building was designed to have three floors, a support structure made out of wood, a central passive ventilation shaft, and hemp/flax insulation in the walls. This building and its wall details are illustrated in **Appendix Figures A.2-3**. The final design specifics and results from the students' assessment included:

- Assumed building life span = 50 yr
- Net living surface area = 266 m2
- Total building material mass = 119662 kg or 449.86 kg/m2
- Total operation energy = 5624 kWh/yr

The embodied land results were compared to a standard Dutch brick house designed by the Netherlands Enterprise Agency and commercial house made of part wood and part straw bales. Since the buildings were designed with different amounts of square meter floor space and functionalities, it was not relevant to compare their embodied land totals. But by taking the amount of embodied land per square meter of floor space, the three solutions were more accurately compared. The bio-based building project had 5.62 ha-year/m^2 with 82% of the materials coming from regrowable and bio-based sources. The standard brick building resulted in having 9.3 ha-year/m^2 of floor embodied land with about 0% regrowable and bio-based materials and the straw/wood building ended up having 9.83 ha-year/m^2 with only 43% regrowable and bio-based materials. Additionally it was found that the material impact had a much larger impact than the embodied or operating energy impact on all of the designs embodied land totals (Rovers, 2012). These results led to the conclusion that materials may be the most influential factor in a solution when considering total embodied land and that there is a balance between the material and energy impact that needs to be further explored.

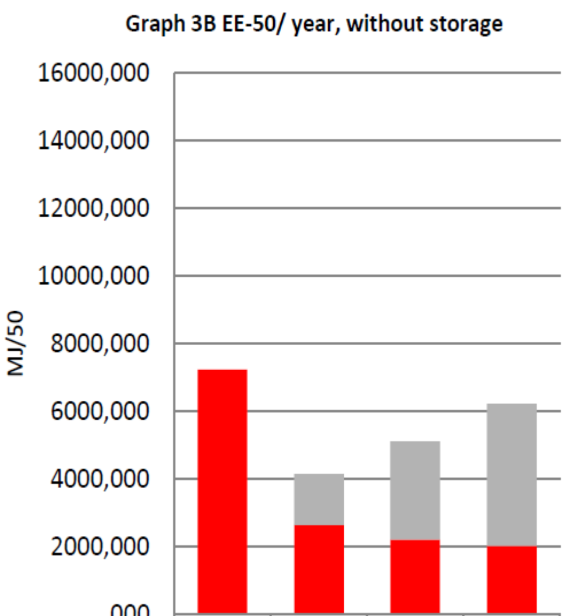
Since the building industry is investing more in passive design standards and various types of insulation solutions for the renovation of existing buildings, additional research was conducted by RiBuilT to explore the relationship between inputted insulation material and energy generation impact. The goal of this research was to find an optimization between the energy demand, energy generation, and material input in order to help inform how far designers should go with insulation.

In a report titled, "Reducing energy demand – or producing more energy?: The role and impact of materials in zero or near-zero energy building & renovation, " one Dutch national standard house built during 1945-65 was used to analyse the material and energy impact of three insulation packages over a 50 year lifespan as a part of a renovation strategy. The building selected was representative of typical terraced social housing design in the Netherlands with 87m^2 of usable floor area and an average of 2.8 inhabitants. The main materials used for the renovation packages were wood fiber and cellulose insulation located within the cavity envelope walls, underneath the floor girders and between the roof girders. Using MAXergy methodology, the existing building envelope with almost no insulation was compared to the three renovation packages. The results in **Figure 2.1** show an optimal ratio between the amount of inputted materials and PV panels used in order to achieve lowest embodied land. Additionally the results from **Figure 2.2** show how the relationship between insulation and PV panel embodied energy impacts displayed a similar optimized curve as the embodied land relationship (Rovers, 2013b) (*Voorbeeldwoningen 2011 Bestaande bouw*, 2011).



	option 0	option 1	option 2	option 3
insul.	,000	747,661	3295,646	3953,011
PV	20687,613	7549,297	6305,884	5785,680

Figure 2.1 Dutch Home Embodied Land Total per Insulation Package (Rovers, 2013b)



	option 0	option 1	option 2	option 3
insulation	,000	1503,888	2902,652	4199,956
PV	7233,491	2639,636	2204,873	2022,982

Figure 2.2 Dutch Home Embodied Energy Total per Insulation Package (Rovers, 2013b)

A later research study titled, “Comparison and development of sustainable office facade renovation solutions in the Netherlands”, used existing cases and expanded on the previous two studies. This MAXergy assessment simulated a south facing office space on which the following three different facade renovation solutions were placed:

- DHV Office
  - facade was completely replaced and the interior was preserved.
  - material applied: aluminium curtain wall; double pane argon filled glazing.
- WNF Office
  - facade was completely replaced and the building was partially demolished and refurbished.
  - material applied: wooden curtain wall; triple pane krypton filled glazing.
- Central Post
  - facade was partially replaced.
  - material applied: aluminium curtain wall; double pane argon filled glazing.

These facade renovation solutions were assessed using multiple methodologies including VABI, ICE, Greencalc+, and MAXergy. Similar to the previous two reports, only MAXergy was able to provide the most complete sustainability assessment in terms of a system’s carrying capacity. The embodied land results from the MAXergy assessment showed that when considering fossil fuels as the source for operation energy, it becomes the most influential factor due to the their significantly higher embodied land than renewable energy sources such as PV panels. When all three solutions were compared using PV panels as the source for operation energy the facade materials embodied land impact was again the most influential factor and WNF solution had the lowest embodied land due to its facade containing more bio-based materials. Using the WNF facade renovation solution, an additional analysis was conducted to determine an optimization strategy for lowering its embodied land even further, which again led to the examination of the relationship between inputted materials and energy impact on embodied land. The following four strategies were used to determine how best to balance the material and energy impacts on embodied land (Ritzen et al., 2013):

1. The original facade after renovation consisting of some bio-based and some non-bio-based materials as well as the necessary operating energy demand.
2. Minimization of material embodied land impact while maintaining the same operational energy demand, thus resulting in 100% bio-based materials.
3. Minimization of the material embodied land without maintaining the operational energy demand, thus resulting in a facade consisting of a plywood sheet and no openings.

4. Minimization of the operational energy demand by increasing the insulation values of the facade using bio-based materials to achieve a thermal resistance value of 10 m^2·K/W.

The embodied land impact for materials and energy using the four optimization strategies are shown in **Figure 2.3**. in cases 1,2 These results have shown that and 4 the material embodied land impact is still higher than the operation energy impact and even in case 3 the energy impact is very small.

All of these case studies were useful in identifying the major benefits of MAXergy as a sustainability assessment tool and the importance of further exploring the optimization of the relationship between material and energy embodied land impacts. In order to better understand the influence both facade materials and energy have on each other, this paper will be simplifying the assessed element to only a facade, simulating a wider range of thermal performance situations and including the physical PV panel embodied land impact, which was not included in the previous reports.

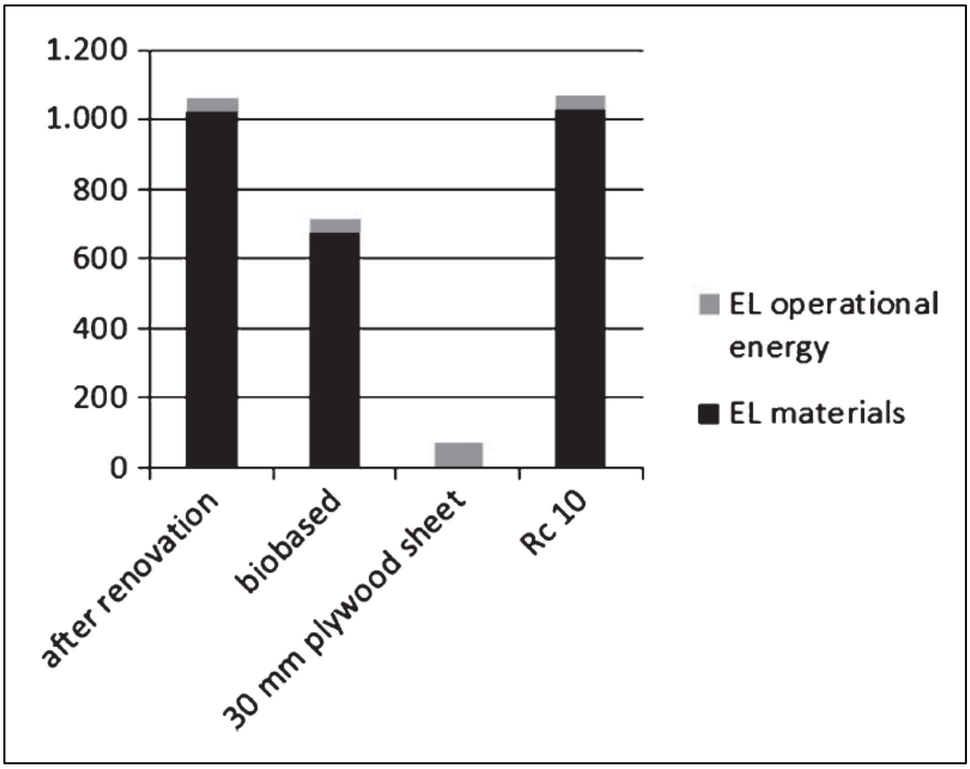


Figure 2.3 Total Embodied Land in m2 of Simulated WNF Solution Renovation Strategies based on Solar Energy and a Lifespan of 30 years (Ritzen et al., 2013)

3 METHODOLOGY

3.1 Prioritizing Material and Energy Resource Management

The main purpose of most building LCSAs being used today is to provide the most accurate and practical results for industry practitioners. Being practical is important because there is already a well-established system of how buildings are designed, approved, and constructed and these sustainable solutions must be able to fit into that system. However, the building industry also has its own agenda of meeting economic and legislative goals in order to survive, which can be relatively shortsighted when considering sustaining humanity for eternity. The question then becomes how accurate or ideal are sustainable solutions that are designed to accommodate industry agendas? Since sustainability is an idealistic concept to begin with and in an attempt to produce the most accurate and objective results possible, this thesis focused on the following priorities when choosing a sustainability assessment methodology.

In general, to sustain human life certain necessities should be considered more important than others based on how long we can survive without them. Logically food and water are the most important resources for survival, followed by shelter and the energy needed to create and sustain them. It can then be said that management of these four main resources should be the focus of an ideal sustainable solution.

As discussed in the state of the art review on sustainable assessments, most international objectives attempt to balance many interconnected economic, social, and environmental impacts, which are more than just the basic necessary resources of survival. Again this can be connected to the influence of the industry's agenda, but it can also be argued that these impacts significantly affect human lives on a daily basis. Ensuring cultural creativity can prosper, technology can advance, and money can be earned has been shown to improve the quality of life, but most of these are subjective and not as high of a priority in relation to humanity surviving physically. On the other hand, the effects of many environmental issues have been proven to be a serious threat to the survival of humanity and should not be ignored. However, if necessary resource management is the root cause of humanity not being able to sustain itself, then the majority of environmental impacts being experienced today are just the consequences/ after effects of this. By creating solutions that attempt to solve the root cause of sustainability problems, then the consequences will no longer exist.

Although management of food, water, materials, and energy are connected and should be considered for the assessment all ideal sustainable solutions, due to time and resource limitations this thesis will exclude food and water management. Only material and energy management will be considered when taking these defined priorities and applying it to specifically assessing the sustainability of envelope wall building solutions.

3.2 Shared Relationship between Materials and Energy: Exergy

A recent four-year study on exergy and spatial planning gave a few insights on the shared relationship between energy and materials. Exergy is essentially a factor representing total amount and concentration of energy (or quality of energy) in terms of being useful for humans. The difference in exergy can be seen when considering the example of trying to power a laptop with a wall outlet and solar cells. The solar cells provide 12 volts of direct current (DC) which is converted to 220 volts of alternating current (AC) for the wall outlet and then back to 12 volts by the laptop. Every time the energy is converted some of it is lost and it will have a lower exergy or energy quality than a direct connection between the solar cell and laptop. In terms of spatial planning the study concluded that the demand of energy should be limited to the supply of renewable energy available within the assessed system location. By realizing the main original source of energy that adds to a system without creating burdens on other connected systems is solar energy, it can be seen as the connection between energy and materials. Everything else used within the system creates more demand and places a burden on the system itself, which reduces its exergy potential (Ny, 2006).

3.3 Closing Life Cycles and 0-Energy Buildings

When considering the life cycle of a building solution it must be assessed as a closed loop if it is to be truly sustained. Closing cycles means more than just reusing or recycling resources; it requires the balance between the supply and demand. With an estimated world population of 9 to 10 billion people by the year 2030 and the current social trend of trying to obtain as many consumables as possible, additional measures will need to be taken. It will be important to ensure that the volume of materials and energy consumed in the building life cycle be minimized as well as closing the cycle. Balance will only be achieved when all cycle inputs are renewable, the cycle is sustained by renewable energy, and the materials used are renewable. The general idea behind closing cycles is to minimize the volume of materials in a cycle, the speed the materials travel through a cycle, and the amount of energy needed to sustain the cycle. In other words consume less and do more with less.

This closed cycle concept carries over into some of the key objectives being pursued by sustainable development initiatives such as the EU commission pushing the industry to develop nearly 0-energy solutions by 2020. 0-energy buildings are becoming increasingly more achievable due to the continued development of solar cell technology and other energy storing equipment. If this goal is actually achieved and building solutions keep progressing in this manner, it can be assumed that building energy use will no longer cause negative environmental impacts since the energy is obtained from renewable sources. The remaining materials connected to the life cycle of the building will be the only remaining burden on the environment. In order to determine an optimized sustainable building solution the assessment should find a balance between the materials and energy use.

3.4 MAXergy

The method of maximizing exergy for materials and energy (MAXergy) was developed in 2010 by Professor Ronald Rovers from Zuyd Univeristy in the Netherlands with the aims to assess how far a solution is from the ideal closed cycle or in other words 0-energy, 0-materials, 0-water, and 0-food. The specific assessment requirements that MAXergy was designed to fulfill focus on achieving maximum objectivity and accuracy. These requirements can be seen in **Table 3.1** (Rovers, 2013a).

Table 3.1 MAXergy Assessment Requirements

Requirement:	Description:
Performance-oriented	Only focus on measuring the use of resources. Social and economic factors are important to the everyday lives of consumers, but can detract from the burdens of resource use, which is being considered as the actual source of sustainability.
Realistic Units	The final score of the assessment is presented in a physical real-world unit. Using arbitrary scores is relative and inaccurate.
Quantitative	Provide scores in absolute quantitative results. Qualitative figures are relative and inaccurate.
Unweighted	Applying percentage weights to any factors is also relative and inaccurate.
Perspective and distance to target	Measure progress towards a future sustainable scenario as opposed to measuring relative improvements from a past non-sustainable scenario.

Table 3.1 MAXergy Assessment Requirements (Continued)

Cause over effect	In order to truly solve a problem, focus on fixing the cause of the problem not the after effects.
Not corrected for climate or human behaviour	Initial designers, producers, and assessors should not be held responsible for the behaviour of product users.
Clear delineation	If an assessment is not understandable or transparent, it will not be practical to use or share with others.

3.4.1 Assessment Boundaries

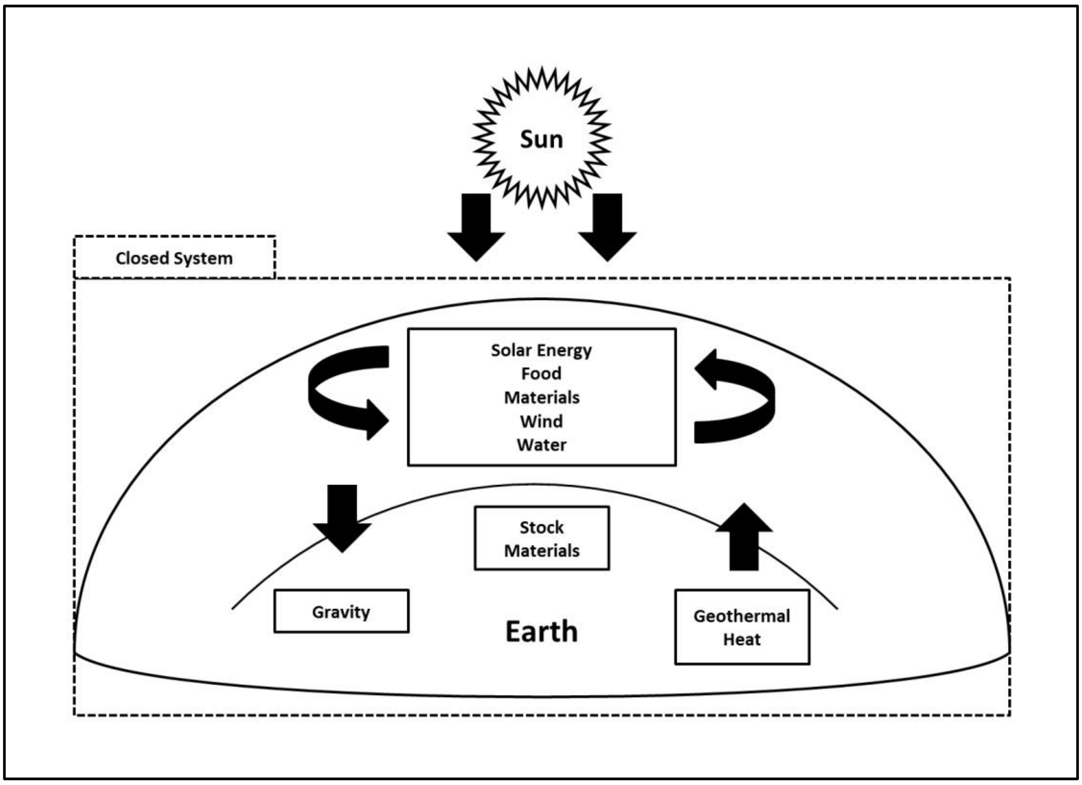


Figure 3.1: MAXergy Assessment Boundary Outline

MAXergy considers the relationship between materials and energy within a closed system on Earth. Using the main principles of exergy, solar radiation is defined as the main external input for creating energy, food and materials. Of course other significant energy sources exist within the planet, but ultimately, with the exception of geothermal heat, these sources such as wind, water, and gravity are all dictated by the sun, which is illustrated in **Figure 3.1**. In order for humans to use this energy (directly or indirectly), land is required and land has limitations such as, typically being used for only one purpose at a time. In order to ensure the cycle of a system is closed it is necessary to have enough land to perform the required functions of the system. This means that land or the embodied land of a product is the physical representation of the connection between energy and materials.

3.4.2 Embodied Land

Typically energy is measured in kilowatts and materials are measured in kilograms, which makes it difficult to compare them to each other. However, since the common basis for comparison between these two components is their embodied land, they can both be converted to square meters of land surface area used. But, this leaves questions such as how much solar energy can be generated on how many square meters of land? In order to solve this issue time must be considered, which is very simple when applying to energy, but becomes more complicated when applying to materials.

Different materials require different amounts of time and space to grow, accumulate, or form. This concept can be applied to all materials, even the more industrial building materials that are not grown in agriculture such as steel, aluminium, and iron. It is not always easy to find consistent and accurate harvest figures, because they are often dependent on a variety of local soil types, climate, and cultivation practices. Also this data is fragmented since different materials hold more importance in different industries such as, forestry, agriculture, and construction.

For the purpose of MAXergy, time is measured in years in order to better represent the growing times for materials and generation times for energy. The final unit that is used for analysis and comparison is space-time in m^2 - year or ha-year. If the function of materials and energy are spread out over more than one year then the amount of embodied land will automatically decrease, but in order to ensure a closed cycle solution, excess resource claim must not be left over after the functional period.

The maximum standard building solution life span used for this assessment and calculations of embodied land used was 50 years. This decision was based on the reasoning that people typically live independently from the age of 20 to approximately 70, which is a total of 50 years. Additionally people normally occupy a workspace from the ages 16 to 66 which is also 50 years.

3.4.3 Embodied Land Tool

In order to calculate the embodied land associated with a product and how far away a solution is from an ideal sustainable closed cycle, The Embodied Land Tool (EL Tool) was developed using Excel. The EL Tool calculates the sum of total embodied land for a solution or in the case of a building, the ha-year required to "regrow" the same building. The preliminary results discussed in the state of the art have shown that the less materials used, the less space-time will be required, and the closer the solution is to a closed cycle (Rovers, 2013a).

Total embodied land consists of the sum of direct embodied land (EL Direct) and indirect embodied land (EL Indirect) as seen in **Equation (3.1)**. EL Direct consists of the physical land required to grow or generate a resource as well as the physical footprint taken up by the product and energy source. EL Indirect is the land needed to satisfy the embodied energy used to produce, manufacture, and install the materials and the energy required to operate the product. Also, materials will need to be returned to the closed cycle at the end of their life span and for certain materials this may require a different physical process or return energy than what was accounted for during the initial stages of the material's life. Since this return embodied land could be derived from either an energy-consuming process or physical land requirements, it could be considered either direct or indirect embodied land. But, if any energy or land required outside the initial phases of a materials life cycle is to be considered indirect embodied land, then this return embodied land (EL Return) will also be categorized as the same. In the end, this categorization only benefits organization and does not alter the final EL Total results. The EL Tool also allows for the inclusion of the space-time needed to regrow the tools used in the various processes. Although, this starts to become too complicated to follow and insignificant in terms of affecting the final results, therefore it was not considered for this assessment.

$$\mathbf{EL\ Direct + EL\ Indirect = EL\ Total\ (ha \cdot year)} \qquad \textbf{(3.1)}$$

$$\text{EL Direct: product footprint; material production footprint; energy supply footprint}$$

$$\text{EL Indirect: operational energy; material embodied energy; material return EL}$$

3.4.4 Energy Supply

Energy can enter a system in many different ways such as wind, hydropower, and biomass but as a practical choice for this methodology, energy is assumed to be delivered as electricity via polycrystalline photovoltaic (PV) solar cells with a $1m^2$ footprint per panel. As this methodology continues to be developed and improved additional modes of energy delivery will be considered as options. Since the panels themselves are materials and need to be accounted for, a panel direct and indirect embodied land total is calculated and divided by its life span of 25 years.

3.4.5 Operational Energy

In relation to the total amount of energy used for a very resource- and energy-intensive product life cycle, such as a building, operational energy is the most significant. In order to calculate the total operational energy required for this thesis's envelope wall assessment, it is necessary to determine the required number of solar panels needed to meet the final energy demand to compensate for the solution's thermal performance. This is referred to as the demand impact or DI. Additionally, the DI is added to a system or storage impact (Sodagara et al.) that represents the energy from the solar panels that needs to be stored.

Since the MAXergy methodology assumes that future energy supplies will be solar-based, it is important to account for storage impacts rather than assuming the building is connected to the grid. Additionally this also allows a more accurate comparison with alternative storage options such as biomass.

3.4.6 Recycling

According to the MAXergy principles, recycling is considered extra energy that can extend the useful lifespan of a material. This only applies to either new building materials or reused materials that have a detailed record of its previous uses. Typically it is difficult to consider recycling for older materials because their origin, life span, and burden are unknown and thus they are usually treated as brand new materials. For future development of the EL Tool, recycled material database templates should be developed for the integration of solution-specific recycled materials.

3.4.7 Comparison to Other Tools and Databases

Of all the numerous sustainability assessment tools existing today, very few accurately measure the source impacts on resources. Most use subjective scoring, weighting factors, and compare solutions to old references. This leads to various elements being arbitrarily combined together. In some cases repetitive accounting for the same issue can occur and consist of very complicated calculations that have low transparency.

MAXergy differs by fundamentally focusing on achieving a closed cycle within a particular space that ensures resource use for an infinite period of time rather than assess absolute uses of resources and optimize life cycles.

In order to help facilitate the MAXergy methodology and Embodied Land Tool calculations a database containing resource properties has been developed. The MAXergy database and its application is very similar the two existing assessment methodologies, Life Cycle Assessment (LCA) and Ecological Footprint. Comparisons between these three approaches are shown in **Table 3.2** and **3.3,** which better distinguishes them and helps justify the use of MAXergy and The Embodied Land Tool over the others.

Table 3.2 LCA vs Embodied Land Tool (Rovers, 2013a)

LCA	Embodied Land Tool
Many common database tools such as Ecoinvent, SimaPro, MRPI, and ICE are used for LCA calculations	Does not account for environmental effects directly.
Environmental effects of all processes for various life cycle phases of a product are weighted together for a single score of total impact. These weighting factors are subjective and using them to obtain one final score lacks justification.	
Every phase of lifecycle has a consecutive increase in margin for error. All the effects are a consequence of the use of a specific resource and not the cause, which can lead to repetitive accounting of life cycle inputs.	Considers inputs and causes of resource cycle instead, which ensures no repetitive accounting of cycle inputs.

Table 3.3 Ecological Footprint vs Embodied Land Tool (Rovers, 2013a)

Ecological Footprint	Embodied Land Tool
Gives results in average hectares needed per person/city/region/country/etc.	Gives results in absolute hectares needed per product or service.
Links actual burden to hypothetical user behavior. This lacks justification as an accurate representation of the functions that cause the burden.	Does not account for subjective human behavior and focuses on assessing the actual function of a product.

Table 3.3 Ecological Footprint vs Embodied Land Tool (Rovers, 2013a)(Continued)

Embodied footprint = global hectares needed to make one ton of a product per year. Compares consumption of resources in hectares to total available land in the world. Results are per spatial system, which can be distorted by imports and exports.	Embodied land is represented as returns of solar energy converted to usable resources per specific location (not an average). Bases assumptions and solutions on the immediate local energy, materials, and space.
Considers resource production, consumption, and waste. Includes the ecosystems ability to process the waste. Waste is represented by greenhouse gases and their absorption by ocean and vegetation. This is a combination of end-of-life effects and causes, which is repetitive and lacks justification of accuracy.	Avoids combing input causes and end-of-life effects.
Only considers resources that can renew themselves within human time scale and does not account for resources that fall out of this category and resource exhaustion.	Considers both resources that can and cannot renew themselves within human time scale and resource exhaustion.
Not able to justify results as an indicator of how sustainable a country or person is in terms of preventing resource exhaustion.	In society can be overruled by monetary valuation system.

3.4.8 System Limitations

MAXergy can be applied to a system of any size. In most cases the embodied land calculations for the various functions of the product actually dictate the final size of the system needed. Additionally the amount of functions that can fit within a specific system can be calculated. For example, preliminary results have shown approximately 2 single family homes with a lifespan of 50 years and their embodied land can fit inside one hectare (Rovers, 2013a).

When using MAXergy for a larger scale system such as a neighborhood, town, or city, existing burdens must be integrated into the analysis. The resulting solution should determine how the combined burdens can be reduced in order to satisfy the existing system limits.

Sensitive aspects and system limitations of MAXergy include allocation, and nutrient and organic material balance in soil. Crops have multiple parts that can be harvested for various products besides building materials. Most of the time, the entire crop is not harvested for the portion being considered for the embodied land calculation and therefore the question arises: how much embodied land should be allocated to the percentage of crop used? The four allocation options in **Table 3.4** have been discussed during the development phase of this methodology and are continuing to be researched and improved.

The most accurate and practical approach for allocation would be to find an optimized balance between satisfying the product's material requirements and trying to achieve 100% useful yield on the land. This would require the integration of local agricultural data such as soil type assessments, a list of crops available for cultivation based on soil type and climate, possible cultivation practices and soil maintenance requirements.

At the moment acquiring this data from any given product location is difficult due to the lack of a consolidated database and inconsistent records containing the above mentioned factors. Therefore, a product material requirement based approach is the most feasible and will be the only one considered for allocation. Specifically out of the four options mentioned in **Table 3.4**, option 2 will be used in order to allow for embodied land reduction factors only when proof of third parties using remaining crop yields can be provided.

In addition to the allocation of crop yields, soil nutrient and organic matter maintenance must be addressed as it is a vital component of sustaining the harvest of crops from the same land. In standard agriculture, nutrients are replenished in the soil via natural water and dust cycles, but they can also be supplemented by a portion of remaining crop yields and purchased fertilizers. For the purpose of the MAXergy embodied land and allocation assessment, only a portion of the remaining crop yields will be considered for soil maintenance. The reason purchased fertilizers are being left out of the assessment is because they would be considered as an additional external input, which goes against the principle of creating an ideal self-contained closed cycle system.

Table 3.4 MAXergy Allocation Options (Rovers, 2013a)

Allocation Option #:	Description:	Discussion:
1	Entire hectare is allocated to the product yield and remaining yield is considered to be unused.	Does not allow for optimization. One type of bamboo can have a product yield of 50% and another type can have 75%. Both would be allocated the same amount of hectares, when in reality one type allows for more alternative functions per hectare.
2	Percentage of hectare allocation for the product yield is reduced if remaining yield can be proven to be used by a third party.	This second option is the same as the first but allows for optimization when the use of remaining yields can be accounted for.
3	It is assumed that the product yield is used and remaining yield is used by third parties. The allocation of hectares is based on their percentages.	The third option calculates net land use and does not require the use of remaining yields to be accounted for.
4	It is assumed that the remaining yield is used to produce energy for the product system.	Option four solves the problem of allocation, but actually decreases the exergetic potential of the resources. If the remaining yields are converted to energy this usually means they are burned, which immediately consumes the high quality energy of the mass. This goes against the principles of closed cycle systems, where mass should remain mass for as long as possible in order to maximize exergy within and slow the cycle speed of the product system.

3.5 Netherlands Envelope Wall Solution Specifications

Since buildings use a variety of material solutions depending on their situation, it is very difficult to compare multiple buildings in their entirety and achieve accurate and objective results. Instead, only envelope/ exterior wall elements based on existing NL building solutions were defined and then adjusted to meet the same criteria in order to compare them in the same theoretical situation. The comparison criteria were assigned as follows:

- Local location: The Netherlands
- Functionality: create building envelope, achieve the same thermal resistance (R-value) for a range of $3.5 \leq R \leq 10$ during the winter months in the Netherlands
- Size: 3 x 6 m wall element (insulation thicknesses were allowed to vary in order to achieve the specific R-values)
- Solland Solar Sunweb PV cell panels with a footprint of $1m^2$ were used as energy supply to compensate the heating demand for each wall solution at the various R-values (*Solland Solar Cells*, 2015).

Since the strength capacities of each wall element were not being compared their connections with structural construction components were also not considered. The main comparison of the assessment focused on the total embodied land per solution at each R-value. The starting R-value of $3.5m^2K/W$ was chosen for this range because according to the Netherlands Building Decree (*Bouwbesluit*, 2012), it is the minimum R-value for envelope closed elements (not including windows or doors). By comparing all the solution's EL results to one another, certain trends formed showing which materials contain lower EL than others. A range of thermal resistance levels were chosen versus just one in order to find the lowest possible EL based on the changing ratio between insulation needed to reduce energy demand and PV panels needed to meet that demand.

3.5.1 Hemp/Flax Wall Solution

The first envelope wall solution considered was based on the previously discussed RiBuilT 100% bio-based building. The solution was designed with the goals of MAXergy in mind and therefore used mainly regrowable materials. A combination of natural hemp and flax was chosen for the insulation layer and douglas fir wood was selected for the timber box frame. The frame was held together using wooden dowels and both the external and internal finishing layers were defined as gypsum wallboard. The reference detail figures for this wall solution are included in **Appendix Figures A.2-3**. These original details were not changed for this paper's assessment, but the insluation thickness was adjusted in order to meet the specific range of R-values. This solution was labeled as the hemp/flax or HF solution for the assessment and its details can be found in **Tabl 3.5**.

Table 3.5 Hemp/Flax Wall Solution Details

Aspect	Details	Source
Cross Section Dimensions	17mm gypsum exterior plasterboard 166mm hemp/flax natural insulation 17mm gypsum interior plasterboard	(*District of Tomorrow Phase Document MAXergy: Final Design > Work Preparation*, 2013)
Frame	200 x 200mm Timber (douglas fir)	
	Wooden dowel connectors	
R-value	5 m2K/W	

3.5.2 Straw Wall Solution

Table 3.6 Straw Wall Solution Details

Aspect	Details	Source
Cross Section Dimensions	2-3mm Buamit mineral external plaster 60mm STEICO Protect (wood fiber board) 0.7mm Siga Majcoat + Tyvek Pro airtight breather membrane 400mm Ecococon straw panel 30mm clay interior render	(Ecococon, 2015) (Baumit, 2015) (SIGA, 2014) (Dupont, 2015)
Frame	45 x 95mm timber 25mm thick fiber board 12mm thick fiber board	
	Paneltwistsec stainless steel screws	
R-value	8.1 m2K/W	

The second envelope wall solution was based on the Ecococon prefab straw panel wall product. Pressed straw was chosen for the insulation layer and a slightly different timber box frame was used, but the same type of wood was assumed to be used for both solutions. The frame in this solution was held together by stainless steel screws. The external finish on the wall was a combination of wood fiber board made by Steico, a mineral plaster made by Baumit, and airtight membranes made by Siga and Tyvek. The internal finish was made from clay plaster. The reference detail figures for this wall solution are included in **Appendix Figures A.4-9**. The original details for this solution were also not changed, but the insulation thickness was adjusted in order to meet the specific range of R-values. This solution was labeled as the straw solution for the assessment and its details can be found in **Table 3.6**.

3.5.3 Brick Wall Solution

Table 3.7 Brick Wall Solution Details

Aspect	Details	Source
Cross Section Dimensions	100mm exterior brick (100 x 200 x 50mm) 25mm air gap 0.6mm weather resistant membrane 13mm gypsum wall board 100mm Isofloc 16mm gypsum wallboard 16mm gypsum wallboard	(Endicott, 2015) (Isofloc, 2015)
Frame	50 x 100 mm timber studs @ 406.4mm centers	
	22-guage galvanized steel tie every horizontal stud and every 24 inches vertically	
	6d nails; 8d nails; 45 mm galvanized roofing nails	
R-value	2.87 m^2K/W	

The third envelope wall solution was based on a similar MAXergy assessment done by Haagen (2015), involving Dutch reference home exterior walls. These solutions consisted of different insulation attachments to a brick cavity wall. The different variations of the cavity wall solution included a few different insulation materials and finishings. The detail drawings of these reference solutions can be found in **Appendix Figures A.10-13**. Since the cavity walls required two layers of brick and could stand on their own without a frame, some adjustments were made to make this third brick solution more comparable to the hemp/flax and straw wall solutions. The cavity wall was adapted into a brick veneer wall with only one brick layer as the exterior finish based on solution details provide by Endicott manufacturers. These details are shown in **Appendix Figures A.14-15**. The brick finish was designed to be attached to an insulated timber stud wall with steel connectors. The interior finish on the wall was gypsum wallboard and the insulation was assumed to be cellulose newsprint fibers made by Isofloc, which was used in the original reference brick solutions. The insulation thickness for this solution was adjusted in order to meet the specific range of R-values. This solution was labeled as the brick solution for the assessment and its details can be found in **Tabl 3.6**.

4 CALCULATIONS

4.1 Solution Inputs

In order to proceed with calculating the embodied land (EL) totals of each envelope wall solution, specific characteristics of each wall type had to be defined and inputted into the EL Tool. These inputs included the previously defined assumptions made in order to compare each solution within the same conditions such as a lifespan of 50 years, wall element size of 3x6m, and the requirement of meeting the thermal resistance range of 3.5 to 10m^{2}k/W during the winter months in the Netherlands. These assumptions then lead to the calculation of how much of each material comprised the solutions. These values were calculated using the dimensions and thermal resistance of the insulating materials given from the solution sources.

Table 4.1 Hemp/Flax Solution Calculated Inputs

HF Solution		
R-Value (m^{2}K/W)	Footprint (m^2)	Total Material Weight (kg)
3.5	0.85	777.92
4.0	0.97	830.21
4.5	1.08	882.51
5.0	1.20	934.81
5.5	1.32	987.11
6.0	1.43	1039.41
6.5	1.55	1091.71
7.0	1.67	1144.01
7.5	1.79	1196.31
8.0	1.90	1248.61
8.5	2.02	1300.91
9.0	2.14	1353.20
9.5	2.25	1405.50
10.0	2.37	1457.80

Depending on how far away the original solution's R-value was away from the set assessment R-value, the thickness of the insulation material was altered to achieve each R-value in the assessment range. This new thickness was calculated using each insulation material's thermal conductivity, λ (W/m·K). Then the total volume of each material was converted into total weight using the material density and the physical footprint of each wall was also calculated using the total thickness of each wall per thermal resistance level multiplied by 6m. These key calculated inputs for each solution are shown in **Tables 4.1 – 4.3**.

Table 4.2 Straw Solution Calculated Inputs

Straw Solution		
R-Value (m^2K/W)	Footprint (m^2)	Total Material Weight (kg)
3.5	1.70	1631.48
4.0	1.70	1699.21
4.5	1.70	1766.94
5.0	1.84	1834.67
5.5	2.02	1902.40
6.0	2.20	1970.12
6.5	2.38	2037.85
7.0	2.56	2105.58
7.5	2.74	2173.31
8.0	2.92	2241.04
8.5	3.10	2308.77
9.0	3.28	2376.50
9.5	3.46	2444.23
10.0	3.64	2511.96

The last solution input was the total operation energy required to compensate for the heat loss of the envelope walls for each thermal resistance level. In order to determine the operation energy demands for the wall solutions, an energy performance simulation software was used called Transient System Simulation Tool (TRNSYS, 2015). This software allowed for the calculation of heat loss for one square meter of wall by simulating the average annual outdoor temperatures for a local region. This heat energy was then assumed to be compensated for by an electric heat pump with a coefficient of performance or COP of 6, which is the highest achievable COP according to the Dutch Heat Pump Association (DHPA, 2013). Initially the climate data for Amsterdam, Netherlands and a COP of 6 were used to calculate the amount of required electrical energy needed to be provided by the PV panels, but in a proceeding sensitivity analysis the effects of using the climate data of Porto, Portugal and a COP of 3 were also explored.

Table 4.3 Brick Solution Calculated Inputs

Brick Solution		
R-Value (m^2K/W)	Footprint (m^2)	Total Material Weight (kg)
3.5	1.77	4522.46
4.0	1.89	4568.90
4.5	2.01	4615.34
5.0	2.13	4661.78
5.5	2.25	4708.22
6.0	2.37	4754.66
6.5	2.49	4801.09
7.0	2.61	4847.53
7.5	2.73	4893.97
8.0	2.85	4940.41
8.5	2.97	4986.85
9.0	3.09	5033.29
9.5	3.21	5079.73
10.0	3.33	5126.16

When considering buildings as a whole, heat loss can occur through the following main processes: ventilation, infiltration, radiation, and transmission. Of course if these wall solutions were being evaluated as part of a larger assembly and structure then it would make sense to consider air conditioning systems and internal/ external heat gains. But, since these wall solutions are being compared as isolated elements and not as a part of an entire building the only considered heat loss was through transmission, which is shown in **Equation (4.1)**.

$$\mathrm{Q} = \frac{S \times (T_i - T_o)}{R} \tag{4.1}$$

Q = heat loss through transmission (W)

S = surface area (m^2)

T_i = inside temperature (°C)

T_o = outside temperature (°C)

R = thermal resistance ($m^2 \cdot K/W$)

The indoor air temperatures used for this assessment were based on the current indoor air quality standards, ASHRAE Standard 55 and ISO 7730. According to these standards the optimal range of indoor air temperatures during a building's operation hours is between 20-24°C in the winter and 23-26°C in the summer for the Netherlands (ASHRAE, 2013) (ISO, 2005). In order to simplify only the typical eight months that required heating in the winter were considered (October-May) and all of the wall solutions were assumed to satisfy the minimum indoor air temperature of 20°C. Additionally the optimal indoor air temperatures for a building during non-operational hours was also considered. In order to account for the potential presence of people during non-operational hours, such as a person sleeping within a residential home, ideal indoor air temperature for sleep was researched. According to a research study done by the government body, Public Health England, the recommended indoor sleeping temperature that has minimal health risks is 18°C (Wookey et al., 2014). After determining these two optimal indoor air temperatures, the final energy simulation considered the indoor air temperature to be 18°C for 6 hours of the day and 20°C for the remaining 18 hours.

Table 4.4 TRNSYS Netherlands Climate Heat Loss Simulation Data and Electrical Energy Demand per R-Value

R- Value ($m^2{\cdot}K/W$)	Q per m^2 of wall ($MJ/m^2{\cdot}yr$)	Electrical Energy Demand ($MJ/m^2{\cdot}yr$)
3.5	77.68	12.95
4	67.97	11.33
4.5	60.42	10.07
5	54.37	9.06
5.5	49.43	8.24
6	45.31	7.55
6.5	41.83	6.97
7	38.84	6.47
7.5	36.25	6.04
8	33.98	5.66
8.5	31.98	5.33
9	30.21	5.03
9.5	28.62	4.77
10	27.19	4.53
* 1 Watt Hour = 0.0036 MJ		

By comparing the wall solutions within the same functionality, size, and thermal performance level, the heat loss per square meter and the electrical energy demand will remain constant for each wall type at each R-value. These values can be seen in **Table 4.4**. This allowed for the assessment to focus on comparing the varied amounts of embodied land required by the different materials to achieve the set thermal performance levels.

4.2 Material Direct Embodied Land Calculations

EL Direct represents the physical land taken up by any materials used in the solutions during their life cycle and the physical footprint of the solutions themselves. This includes the materials used for the energy supply as well, which in this case are the PV panels. EL Direct for every kg of material was calculated using kg/ha-yr production yields found typically from mining or agricultural harvesting records. Before this assessment was conducted, most of the solution materials already had their production yields stored in MAXergy's existing material database. By taking the reciprocal of the production yield and then multiplying by 10000 m2 for every ha, the units were converted to obtain m2-yr/kg of EL Direct. This calculation is shown in **Equation (4.2).** These values were then multiplied by the total material weights (kg) for each solution and summed to obtain the Total EL Direct per solution**.**

$$\left(\frac{1}{Production\ Yield\ [kg/ha \cdot yr]}\right) \times \left(\frac{10000m^2}{ha}\right) = EL\ Direct\ [\frac{m^2 \cdot yr}{kg}] \qquad \textbf{(4.2)}$$

4.3 Material Indirect Embodied Land Calculations

Indirect embodied land represents all land required by the energy supply materials to compensate for the embodied energy of all the materials. It also includes the embodied energy or embodied land required to return certain materials back into the solution life cycle if they take too long to regenerate on their own. This return embodied land is typically higher for non-regrowable materials such as fossil fuels and minerals, while it is very low or not applicable to the materials that can be regrown using the same embodied land already accounted for in the EL Direct calculations such as wood, hemp, flax, bamboo, and straw.

The summation of the material EE was then divided by the amount of energy output from a PV panel, MJ/m2-yr, in order to represent the amount of EL Indirect (m2-yr/kg) required to collect the solar energy that compensates the material EE. This conversion is demonstrated in **Equation (4.3)**. The total EL Indirect for each solution was then calculated the same way as the Total EL Direct, by multiplying by the kg used of each material and then summing.

$$\frac{(\sum Production, Manufatction, Installation\ EE) + Return\ EE\left[\frac{MJ}{kg}\right]}{PV\ Panel\ Output\ Energy\ \left[\frac{MJ}{m^2 \cdot yr}\right]} + Return\ EL\left[\frac{m^2 \cdot yr}{kg}\right] = EL\ Indirect\ \left[\frac{m^2 \cdot yr}{kg}\right] \tag{4.3}$$

If the Return EL is derived from process that requires EE then it is calculated using **Equation 4.3**. If the Return EL is derived from a process that requires land that has not already been accounted for in the EL Direct calculations then it is calculated using the same equations as EL Direct but still categorized as EL Indirect. Again, because these values ultimately end up having the same units, this categorization does not affect anything other than the organization of the results. The final EL total will remain the same if Return EL is categorized as Direct EL.

4.4 Energy Supply Embodied Land Calculations

The direct and indirect embodied land calculations for the PV panels for each solution were calculated separate from and after the solution materials EL was calculated. This was due to the number of physical PV panels being dependent on the compensating operating energy required for the wall solutions energy loss per thermal resistance level. Also by keeping these calculations separate from the main solution materials EL calculations, it would be easier to integrate different types of energy supply with different energy outputs such as biofuel, wind, hydro, and geothermal in the future.

The thermal resistance range levels increased in intervals of 0.5. For each level the respective electrical energy demand per 3x6m wall element was divided by the 432 MJ/m^2 energy output of a 1 m^2 PV panel to determine how many panels were required to compensate the heat loss. Once the total number of panels was calculated both the EL Direct and EL Indirect were calculated using the same methods as the solution materials. Although, since the panels have the ability to actually be mounted on building solutions, their physical footprint could be neglected, but since this assessment is only considering isolated wall elements the panel footprint was still included in its EL Direct total.

The final step in calculating the EL Total of the PV panels involved accounting for the panel's shorter lifespan in comparison to the wall solutions lifespan of 50 years. The PV panels only last about 25 years before needing to be replaced. This means that their EL Direct and EL Indirect needed to be accounted for twice within 50 years. The total amount of PV panels and their EL values per R-value are shown in **Table 4.6**.

Table 4.5 Required # of PV Panels to Meet Energy Demand and EL Calculations per R-Value

R- Value ($m^2 \cdot K/W$)	# of Panels (m^2)	EL Direct ($m^2 \cdot yr$)	EL Indirect ($m^2 \cdot yr$)	EL Total (m^2/50yr lifespan)
3.5	0.54	2.68	2321.90	92.99
4	0.47	2.35	2031.66	81.37
4.5	0.42	2.09	1805.92	72.33
5	0.38	1.88	1625.33	65.10
5.5	0.34	1.71	1477.57	59.18
6	0.31	1.56	1354.44	54.25
6.5	0.29	1.44	1250.25	50.07
7	0.27	1.34	1160.95	46.50
7.5	0.25	1.25	1083.55	43.40
8	0.24	1.17	1015.83	40.68
8.5	0.22	1.10	956.08	38.29
9	0.21	1.04	902.96	36.16
9.5	0.20	0.99	855.44	34.26
10	0.19	0.94	812.67	32.55

5 RESULTS

Before the final results were analysed and compared the EL Total for each solution was divided by the assumed 50 year lifespan. This was done because the solutions were assumed to reach a closed loop or net-0 potential in terms of materials and energy within a lifespan of 50 years. This assumption means each solution and their embodied land would be useful for compensating their burden over the course of their entire lifespan of 50 years. The final EL Total results were also converted from square meters to hectares because it is easier to think of land in this unit. So the final presented units of the EL results were in hectares per 50 year lifespan.

5.1 Hemp/ Flax Envelope Wall Solution

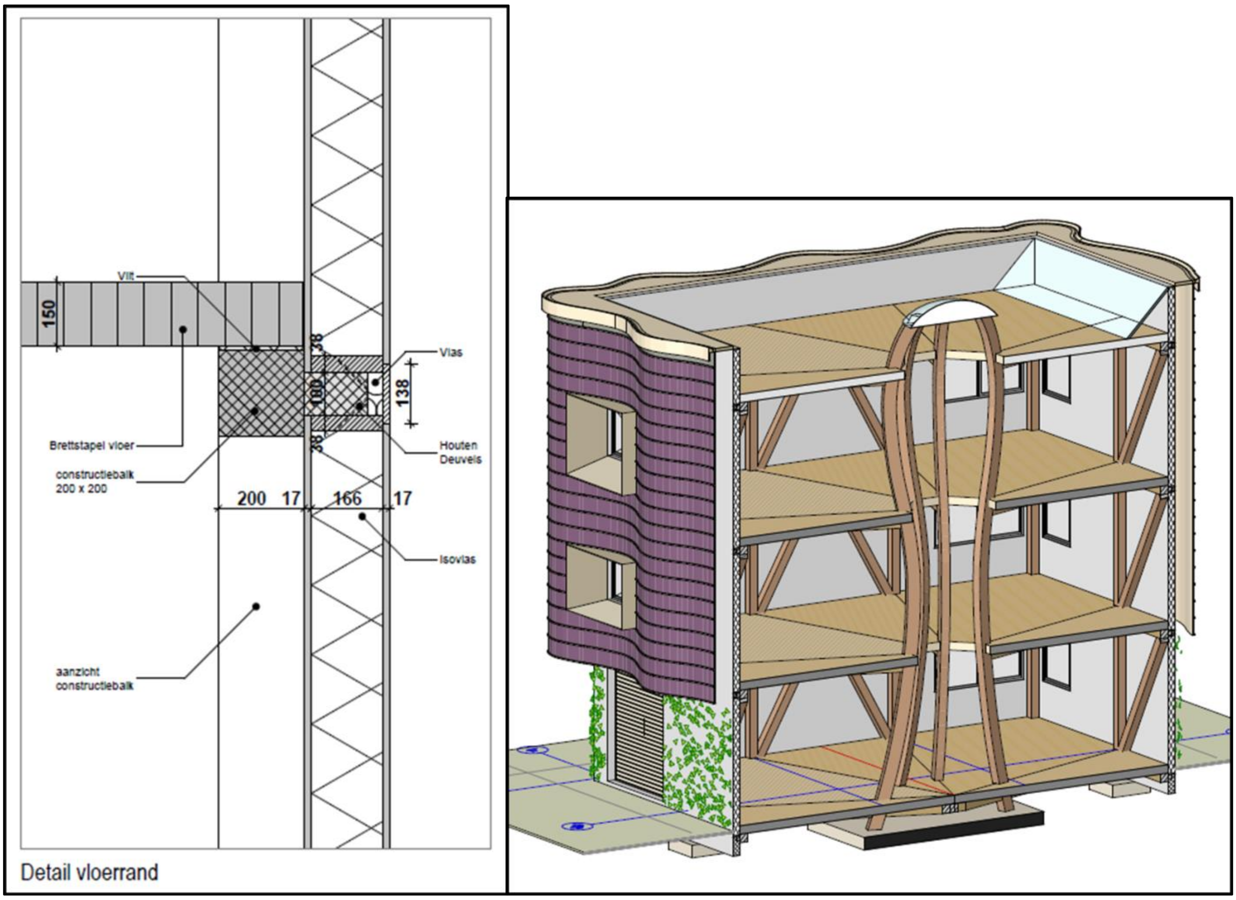


Figure 5.1 Hemp/Flax Solution (*District of Tomorrow Phase Document MAXergy: Final Design > Work Preparation*, 2013)

5.1.1 Embodied Land

The resulting total EL per R-value gave a maximum of 1.19E-02 ha/50yr at the lowest R-value of 3.5 m^2·K/W and an optimal minimum of 9.73E-03 ha/50yr at an R-value of 6.5-7.5 m^2·K/W. The changes in total EL per R-value show a parabolic curve and are displayed in **Figure 5.2**. The insulation that was adjusted for this solution was made of natural hemp/flax fibers and it was supported by a douglas fir wood frame. All of the adjusted insulation and constant materials were considered to calculate the full material impact for the EL Total results. The direct, indirect and total EL per kg of material used in the hemp/flax envelope wall solution are presented in **Table 5.1**. The breakdown of EL Total per R-value into material and PV panel impact can be seen in **Figure 5.3**.

Table 5.1 Hemp/Flax Solution Material Embodied Land Properties

Material	EL Direct per kg (m^2·yr/kg)	EL Indirect per kg (m^2·yr/kg)	EL Total per kg (m^2·yr/kg)
Flax	1.03E+01	9.14E-02	1.04E+01
Hemp	6.55E+00	1.90E-02	6.57E+00
Gypsum Plasterboard	6.06E-01	1.56E-02	6.22E-01
Wood (Douglas Fir)	1.97E+00	1.71E-02	1.99E+00

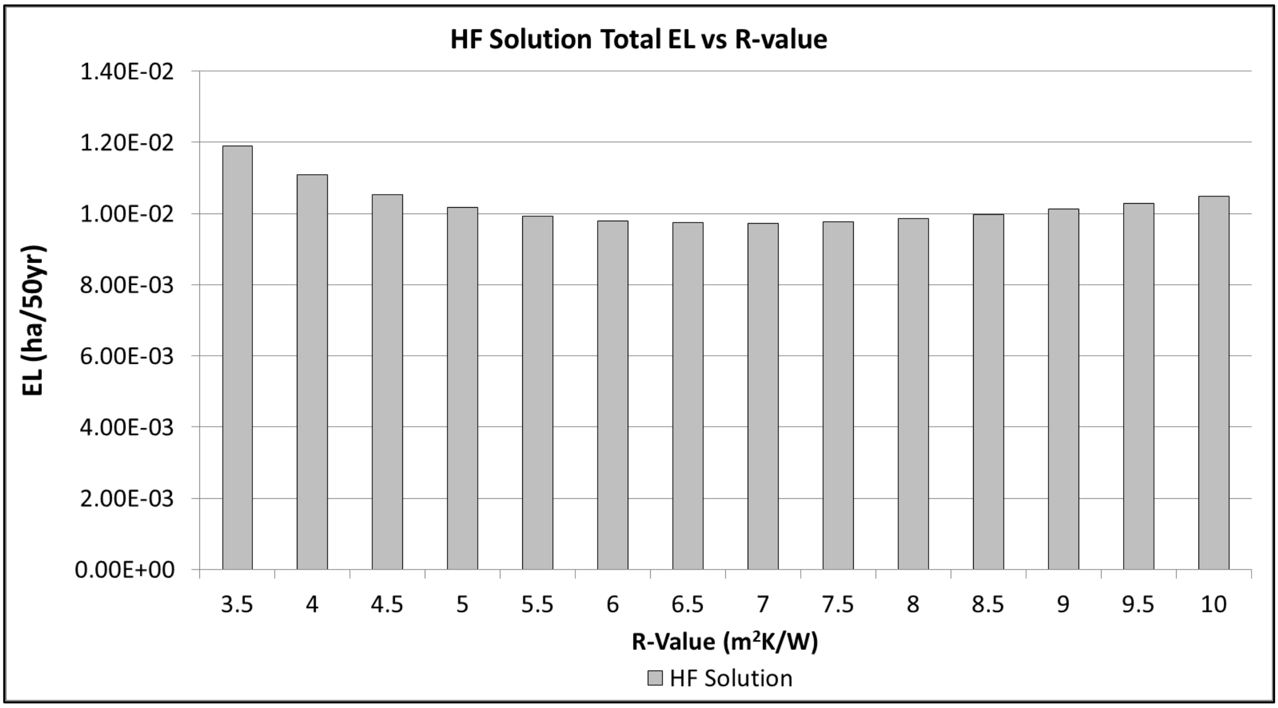


Figure 5.2 Hemp/Flax Solution Total Embodied Land vs R-value

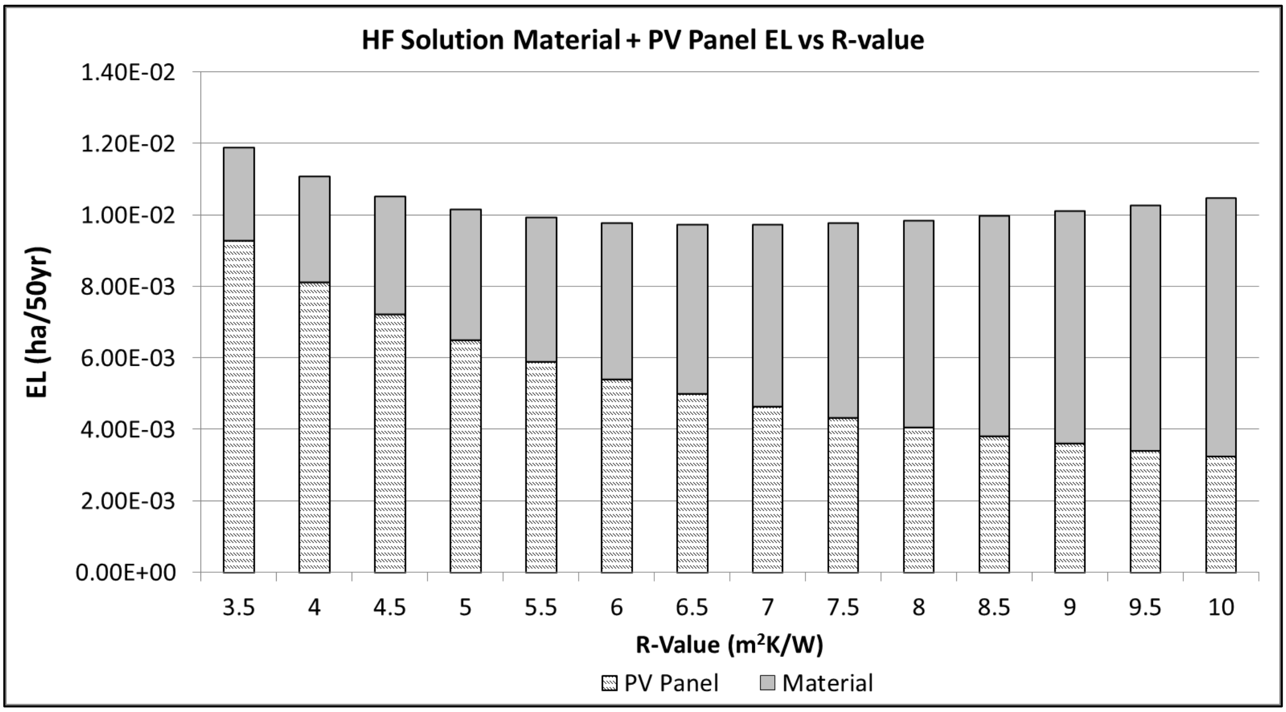


Figure 5.3 Hemp/Flax Solution Material + PV Panel Embodied Land vs R-value

5.1.2 Embodied Energy

The total EE per R-value resulted in a minimum of 155.68 MJ/50yr at an R-value of 3.5 $m^2 \cdot K/W$ and a maximum of 283.26 MJ/50yr at an R-value of 10 $m^2 \cdot K/W$. The changes in total EE per R-value show an increasing linear trend and can be seen in **Figure 5.4**. The EE per kg of material used in the hemp/flax wall solution are presented in **Table 5.2**. The relationship between inputted materials and PV panels per R-value can be seen in **Figure 5.5**.

Table 5.2 Hemp/Flax Solution Material Embodied Energy Properties

Material	EE per kg (MJ/kg)
Flax	3.95E+01
Hemp	8.20E+00
Gypsum Plasterboard	6.75E+00
Wood (Douglas Fir)	7.40E+00

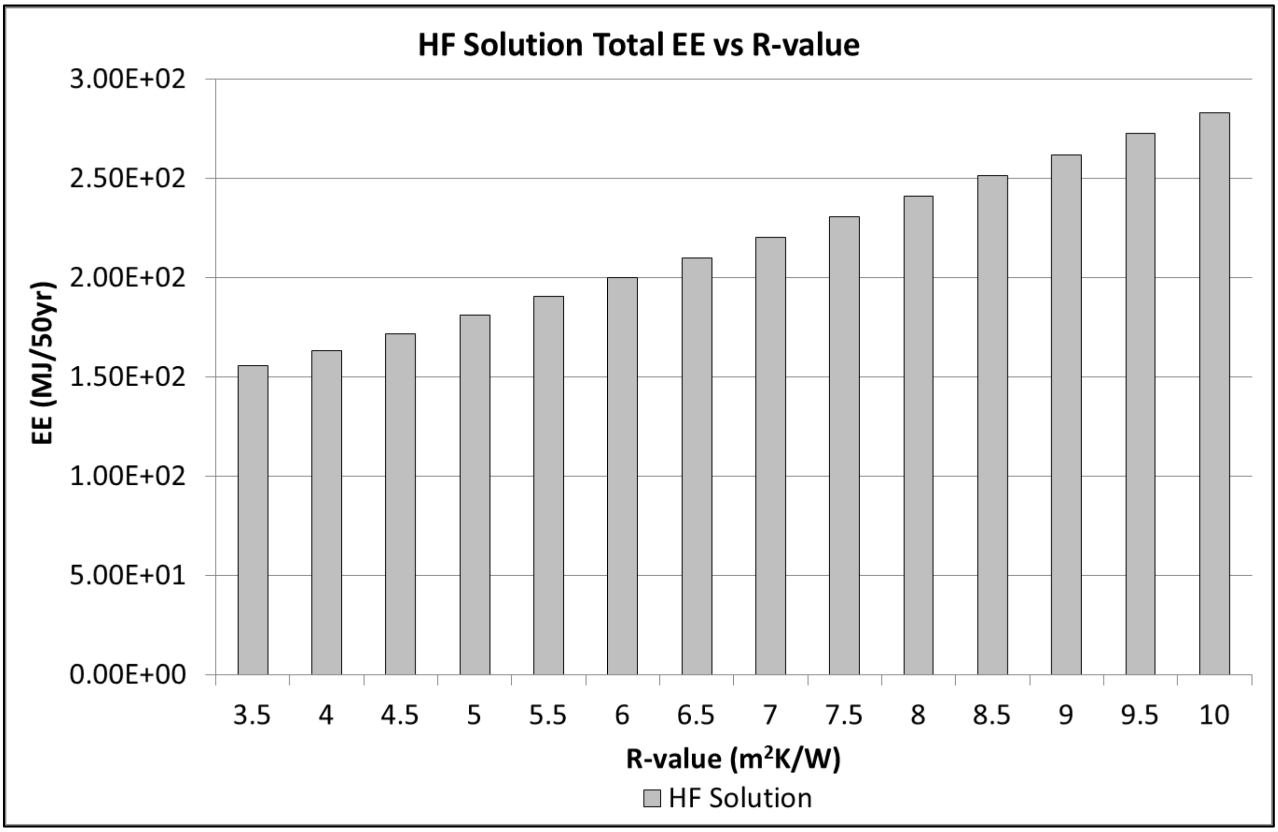


Figure 5.4 Hemp/Flax Solution Total Embodied Energy vs R-value

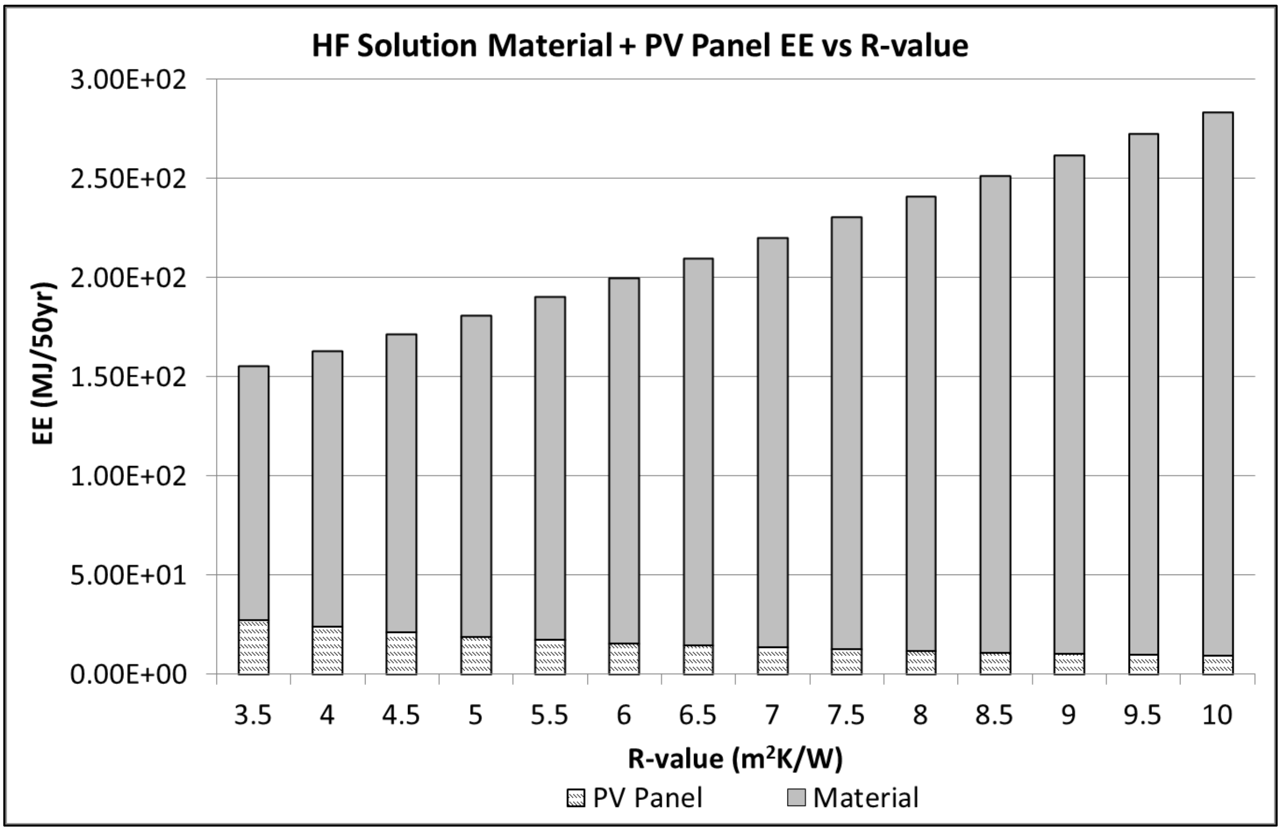


Figure 5.5 Hemp/Flax Solution Material + PV Panel Embodied Energy vs R-value

5.2 Straw Envelope Wall Solution

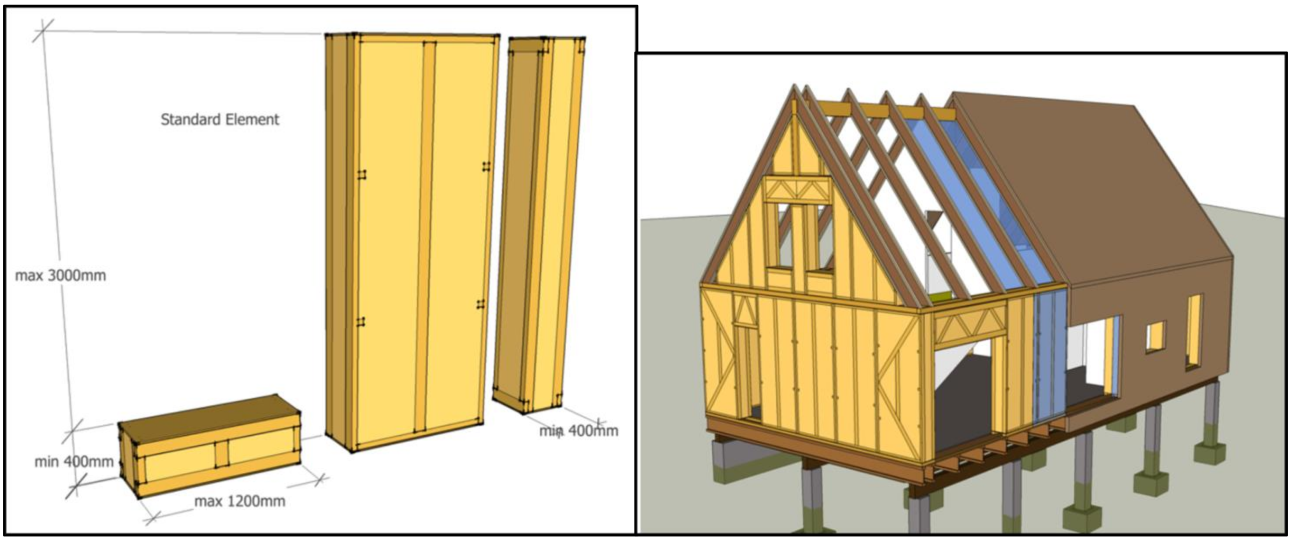


Figure 5.6 Straw Solution (Ecococon, 2015)

5.2.1 Embodied Land

The resulting total EL per R-value gave a maximum of 1.65E-02 ha/50yr at the lowest R-value of 3.5 $m^2 \cdot K/W$ and an optimal minimum of 1.43E-02 ha/50yr at an R-value of 6.5-7.5 $m^2 \cdot K/W$. The changes in total EL per R-value show a parabolic curve and are presented in **Figure 5.7**.

Table 5.3 Straw Solution Material Embodied Land Properties

Material	EL Direct per kg ($m^2 \cdot yr/kg$)	EL Indirect per kg ($m^2 \cdot yr/kg$)	EL Total per kg ($m^2 \cdot yr/kg$)
Clay Render	1.26E-04	6.94E-03	7.07E-03
Lime	2.20E-04	1.23E-02	1.25E-02
Polyethylene	0.00E+00	1.92E-01	1.92E-01
Polypropylene	0.00E+00	2.30E-01	2.30E-01
Steel (Stainless)	1.10E-04	6.13E+03	6.13E+03
Straw	2.50E+00	5.56E-04	2.50E+00
Wood (Douglas Fir)	1.97E+00	1.71E-02	1.99E+00
Wood Fiberboard	3.25E+00	3.94E-02	3.29E+00

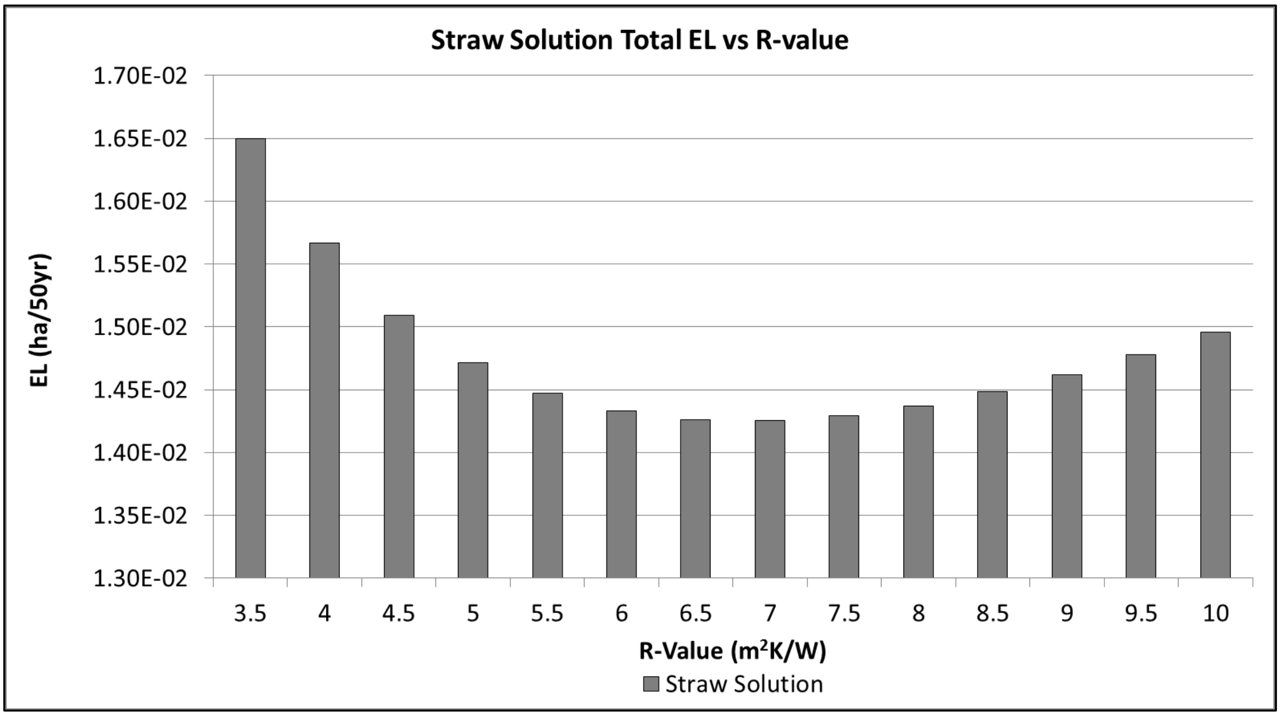


Figure 5.7 Straw Solution Total Embodied Land vs R-value

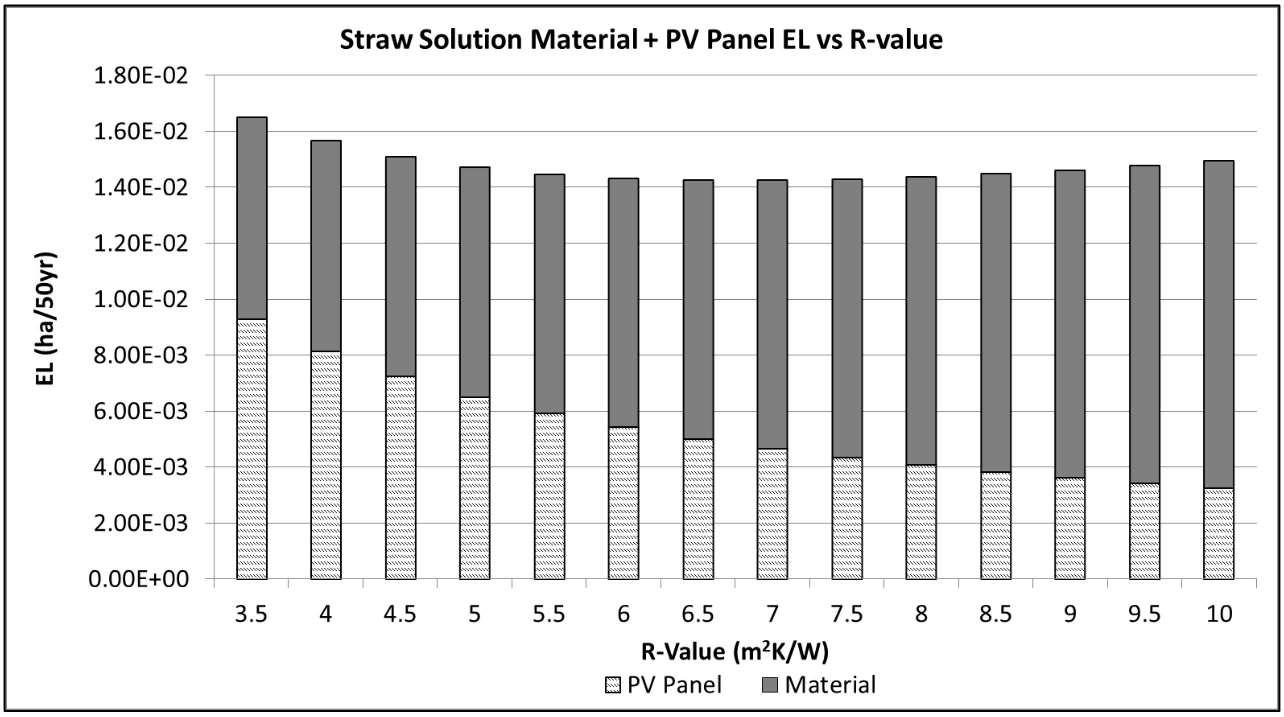


Figure 5.8 Straw Solution Material + PV Panel Embodied Land vs R-value

The insulation that was adjusted for this solution was made of prefab pressed straw panels and it was supported by a douglas fir wood frame. The direct, indirect and total EL per kg of material used in the straw envelope wall solution are presented in **Table 5.3**. The relationship between the material and PV panel impact per R-value can be seen in **Figure 5.8**.

5.2.2 Embodied Energy

The total EE per R-value resulted in a minimum of 196.20 MJ/50yr at an R-value of 5.5-6.5 $m^2 \cdot K/W$ and maximums of 201.17 MJ/50yr at an R-value of 3.5 $m^2 \cdot K/W$ and 200.30 MJ/50yr at an R-value of 10 $m^2 \cdot K/W$. The changes in total EE per R-value also show a parabolic trend and can be seen in **Figure 5.9**. The EE per kg of material used in the straw wall solution are presented in **Table 5.4**. The EE relationship between inputted material and PV panel impact per R-value can be seen in **Figure 5.10**.

Table 5.4 Straw Solution Material Embodied Energy Properties

Material	EE per kg (MJ/kg)
Clay Render	3.00E+00
Lime	1.80E+02
Polyethylene	8.31E+01
Polypropylene	9.92E+01
Steel (Stainless)	3.54E+01
Straw	2.40E-01
Wood (Douglas Fir)	7.40E+00
Wood Fiberboard	1.70E+01

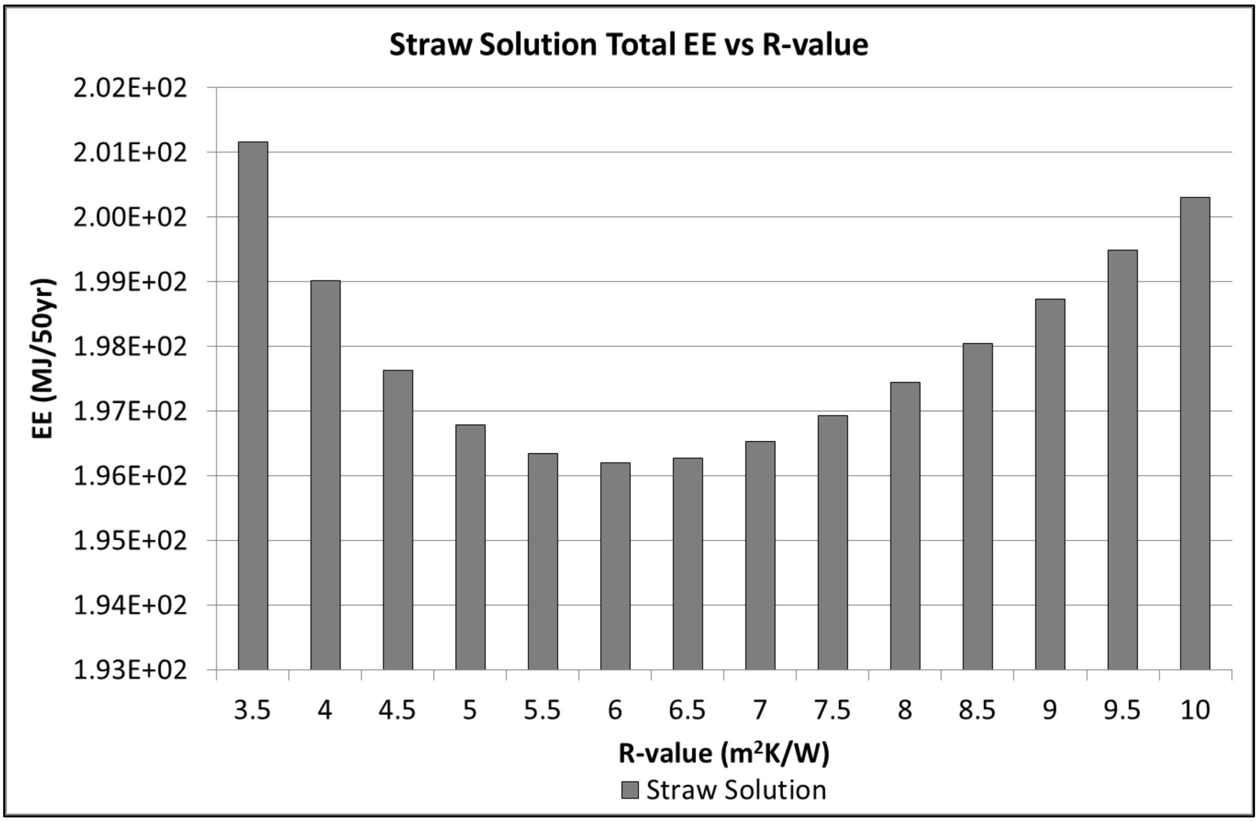


Figure 5.9 Straw Solution Total Embodied Energy vs R-value

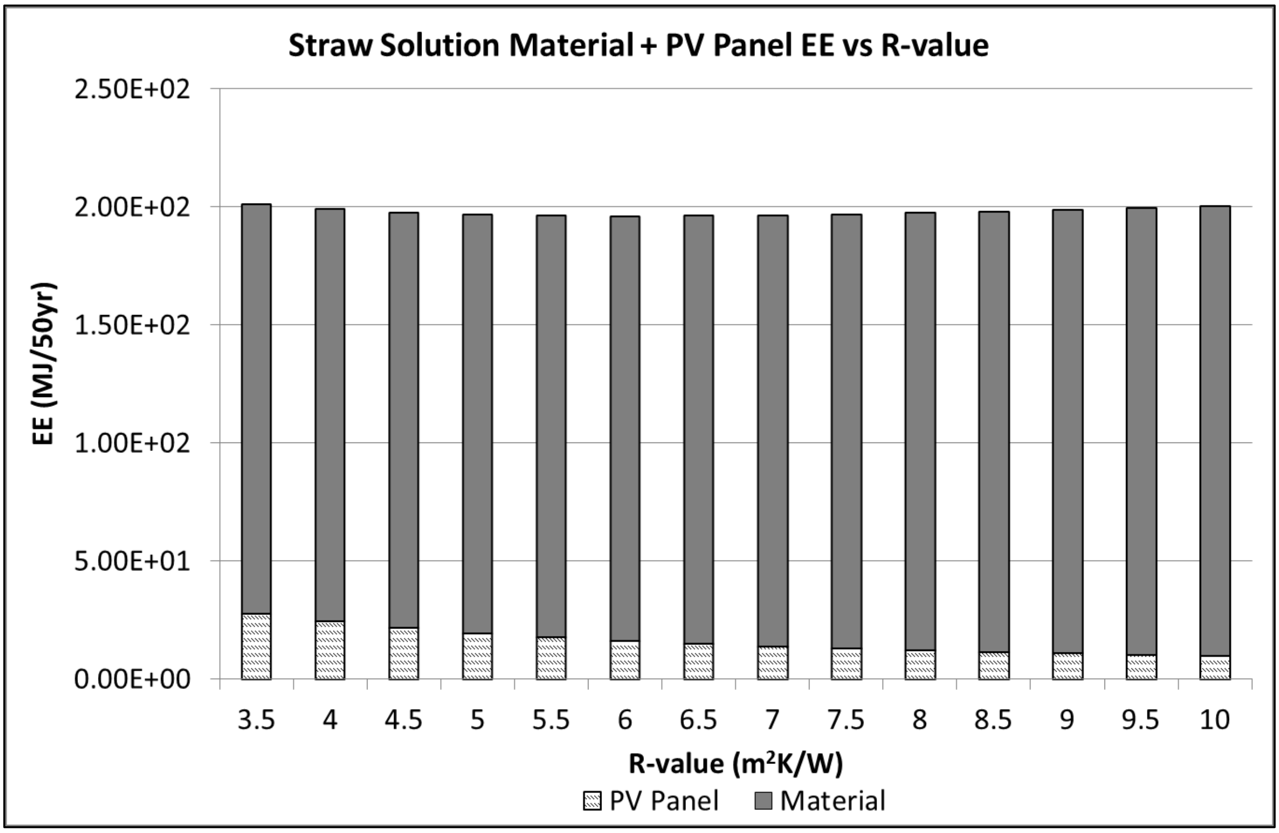


Figure 5.10 Straw Solution Material + PV Panel Embodied Energy vs R-value

5.3 Brick Envelope Wall Solution

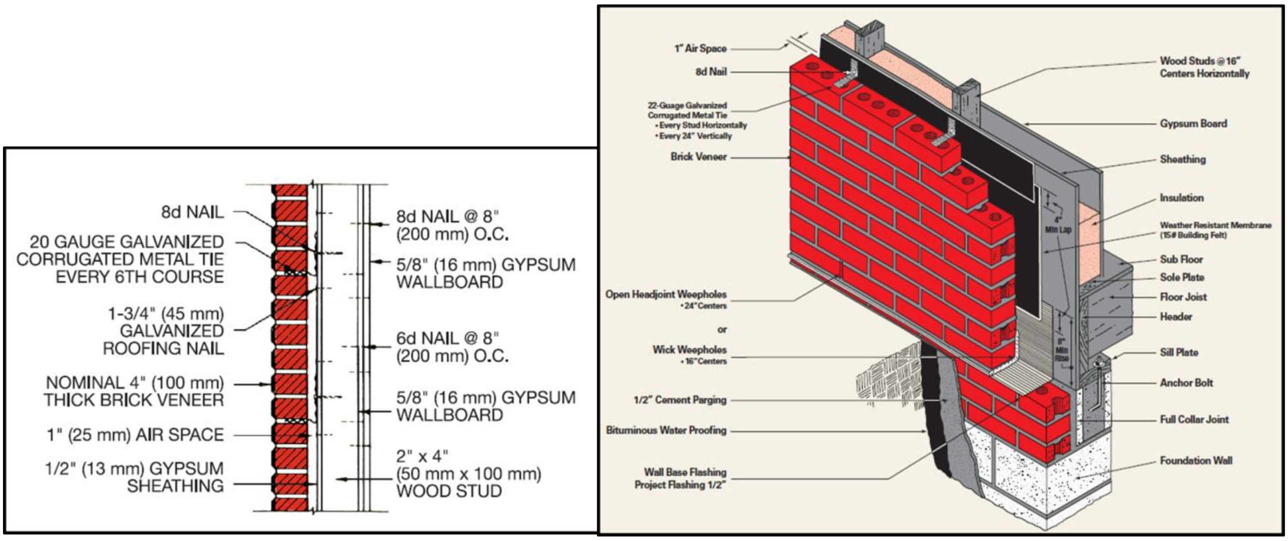


Figure 5.11 Brick Solution (Endicott, 2015)

5.3.1 Embodied Land

The resulting total EL per R-value gave a maximum of 2.67E-01 ha/50yr at the lowest R-value of 3.5 m^2·K/W and an optimal minimum of 2.63E-01 ha/50yr at an R-value of 10 m^2·K/W. The changes in total EL per R-value indicate a hyperbolic curve and are presented in **Figure 5.12**. The insulation that was adjusted for this solution was made of the cellulose fiber composite, Isofloc, and it was supported by a douglas fir wood stud frame. The direct, indirect and total EL per kg of material used in the brick envelope wall solution are presented in **Table 5.5**. The EL relationship between inputted material and PV panel impact per R-value can be seen in **Figure 5.13**.

Table 5.5 Brick Solution Material Embodied Land Properties

Material	EL Direct per kg (m^2·yr/kg)	EL Indirect per kg (m^2·yr/kg)	EL Total per kg (m^2·yr/kg)
Cement	0.00E+00	4.08E+01	4.08E+01
Clay Brick	0.00E+00	6.94E-03	6.94E-03
Clay/ Loam	1.26E-04	6.94E-03	7.07E-03
Isofloc	8.09E-02	4.18E-01	4.98E-01
Lime	2.20E-04	1.23E-02	1.25E-02
Mortar	0.00E+00	7.13E-02	7.13E-02

Table 5.5 Brick Solution Material Embodied Land Properties (continued)

Gypsum Plasterboard	6.06E-01	1.56E-02	6.22E-01
Polyethylene	0.00E+00	1.92E-01	1.92E-01
Sand	8.90E-04	1.88E-05	9.09E-04
Galvanized Steel	1.10E-04	6.13E+03	6.13E+03
Stainless Steel	1.10E-04	6.13E+03	6.13E+03
Wood (Douglas Fir)	1.97E+00	1.71E-02	1.99E+00

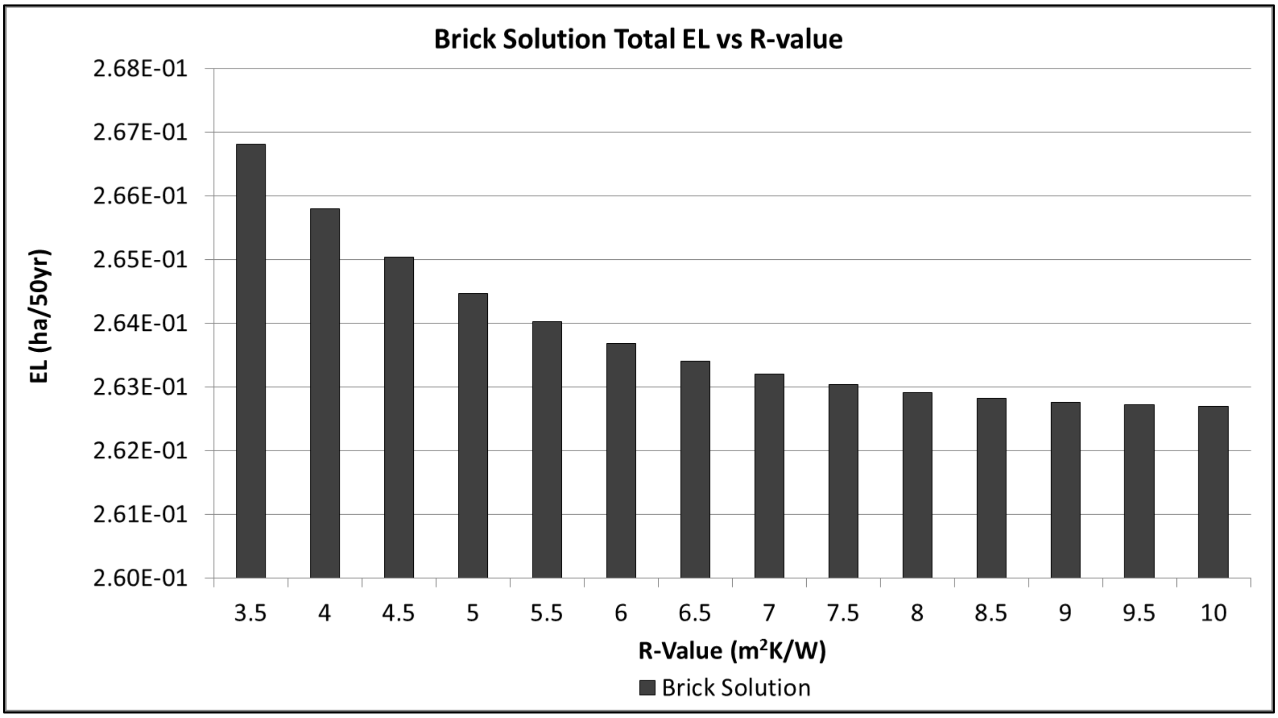


Figure 5.12 Brick Solution Total Embodied Land vs R-value

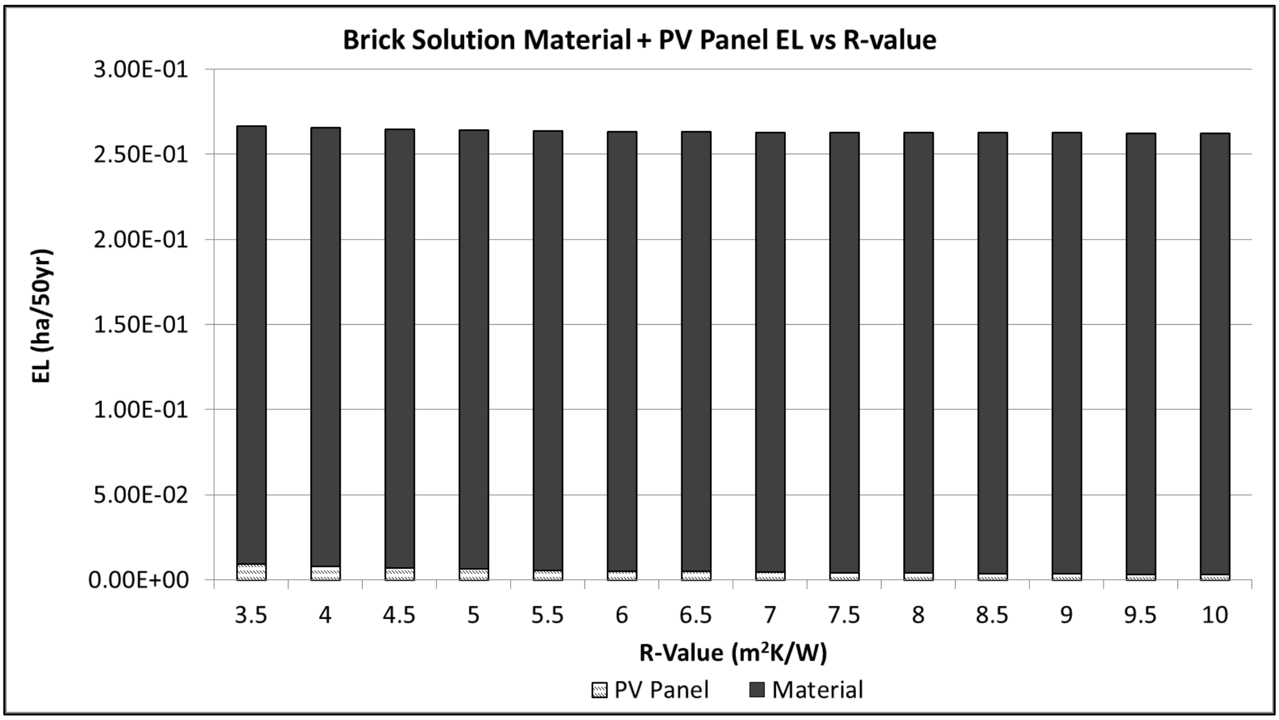


Figure 5.13 Brick Solution Material + PV Panel Embodied Land vs R-value

5.3.2 Embodied Energy

Table 5.6 Brick Solution Material Embodied Energy Properties

Material	EE per kg (MJ/kg)
Cement	4.51E+00
Clay Brick	3.00E+00
Clay/ Loam	3.00E+00
Isofloc	1.80E+02
Lime	5.30E+00
Mortar	3.08E+01
Gypsum Plasterboard	6.75E+00
Polyethylene	8.31E+01
Sand	8.10E-03
Steel (Galvanized)	4.00E+01
Steel (Stainless)	3.54E+01
Wood (Douglas Fir)	7.40E+00

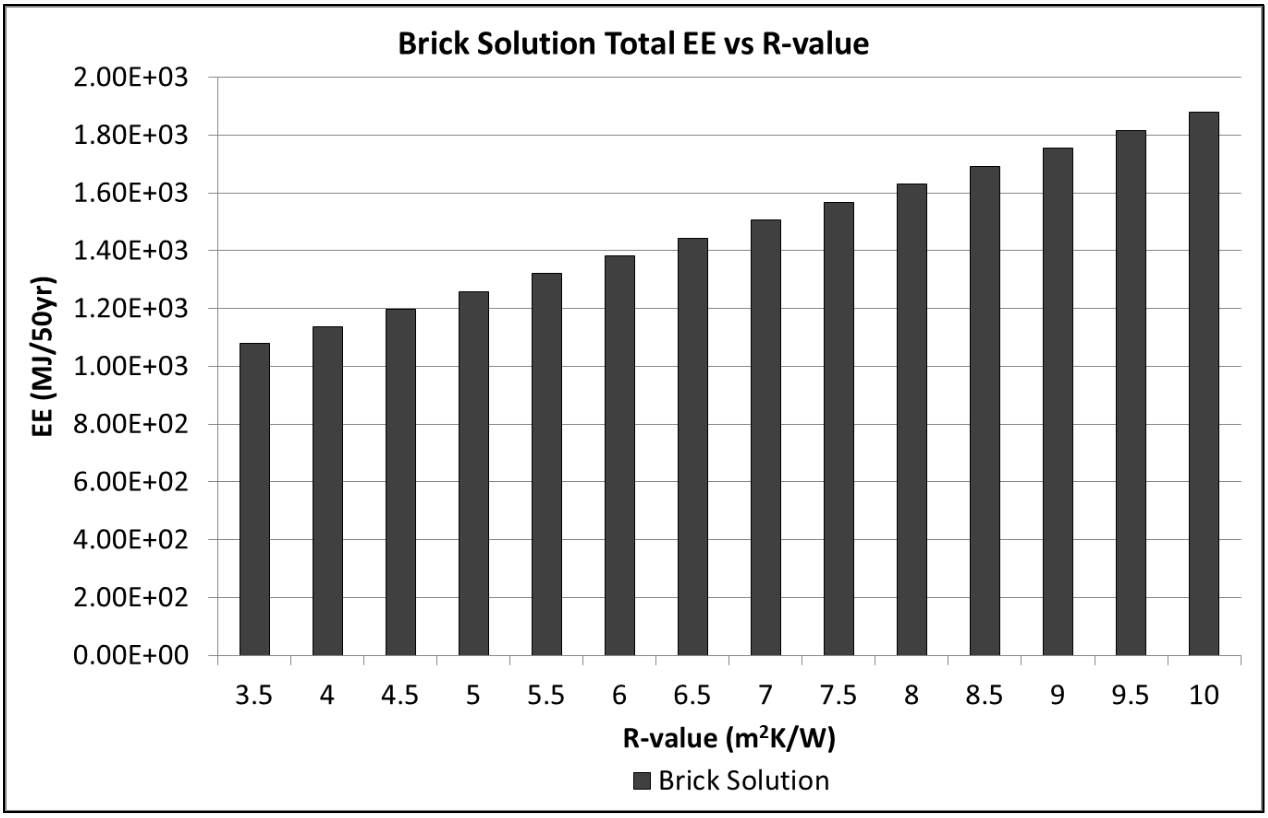


Figure 5.14 Brick Solution Total Embodied Energy vs R-value

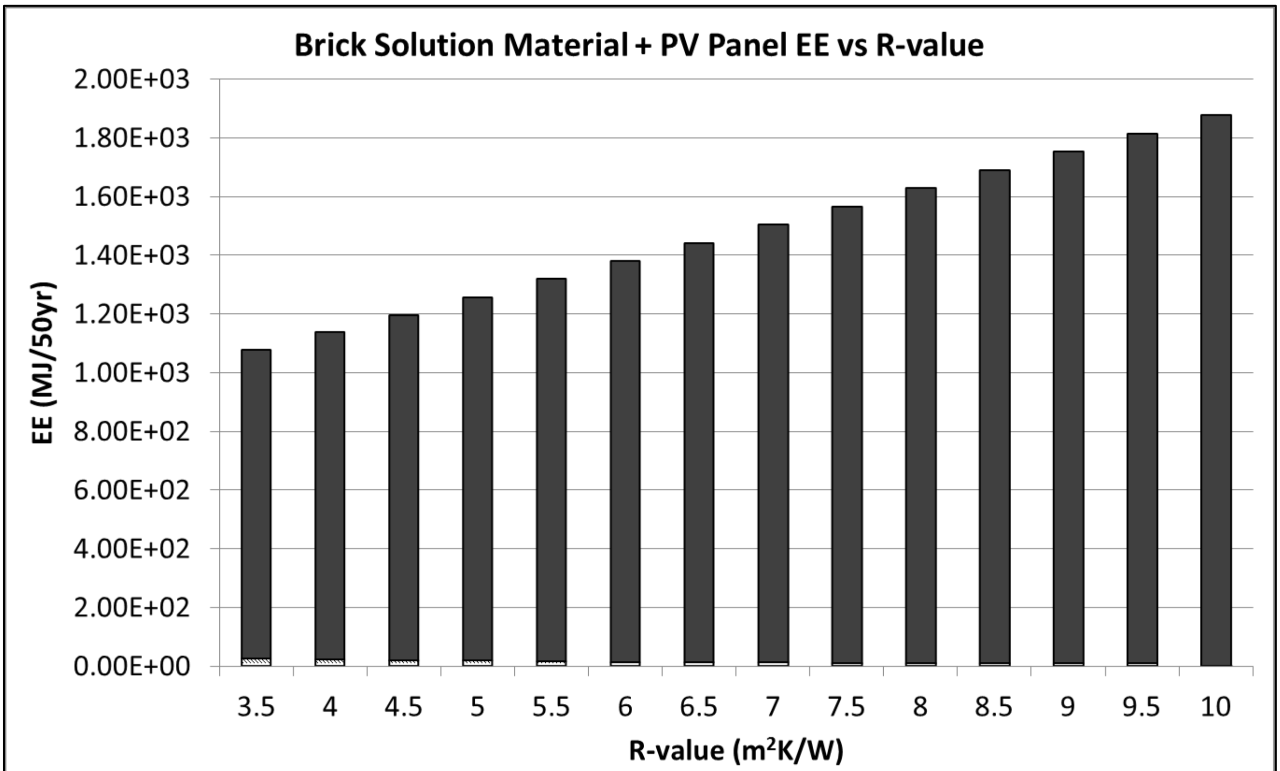


Figure 5.15 Brick Solution Material + PV Panel Embodied Energy vs R-value

The total EE per R-value resulted in a minimum of 1078.61 MJ/50yr at an R-value of 3.5 $m^2 \cdot K/W$ and a maximum of 1878.39 MJ/50yr at an R-value of 10 $m^2 \cdot K/W$. The changes in total EE per R-value show an increasing linear trend and can be seen in **Figure 5.14**. The EE per kg of material used in the brick wall solution are presented in **Table 5.4**. The EE relationship between inputted materials and PV panels per R-value can be seen in **Figure 5.15**.

5.4 Solution Comparison for Total EL and EE

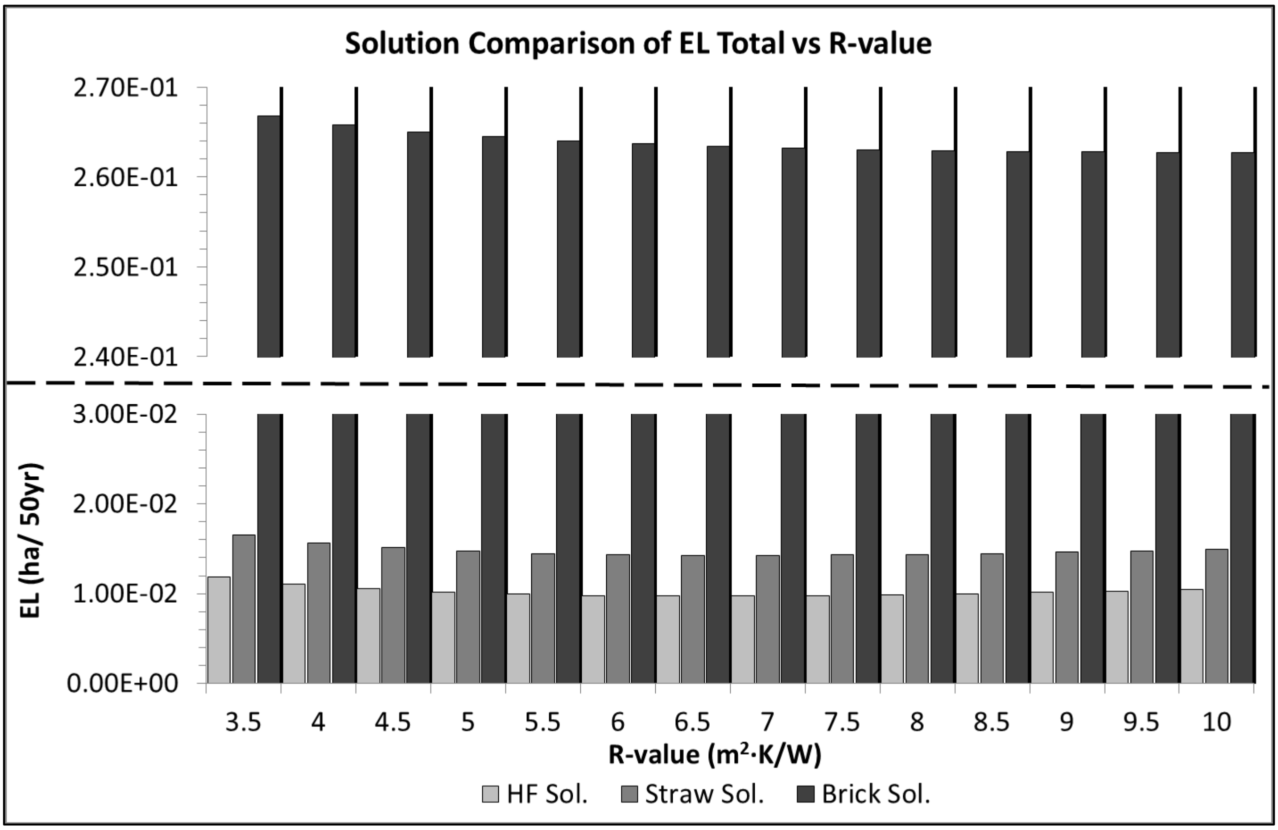


Figure 5.16 Solution Comparison of Total Embodied Land vs R-value

The comparison between solution results showed a significant difference in EL Totals per R-value. On average the straw solution's EL Total was only about 1.44 times more than the hemp/flax solution, while the brick solution EL Total was about 17.89 times more than the straw solution and 25.83 times more than the hemp/flax solution. **Figure 5.16** illustrates the side-by-side EL comparison. In order to relate these MAXergy EL results with the more common sustainability assessments established in the building industry today, separate results were produced that only considered the embodied energy of each solution. The average difference between the straw and hemp/flax solution's EE Total was 0.95 times and the brick solution EE total was about 6.68 times and 7.46 times more than the hemp/flax and straw solutions respectively. **Figure 5.17** shows the side-by-side EE comparison.

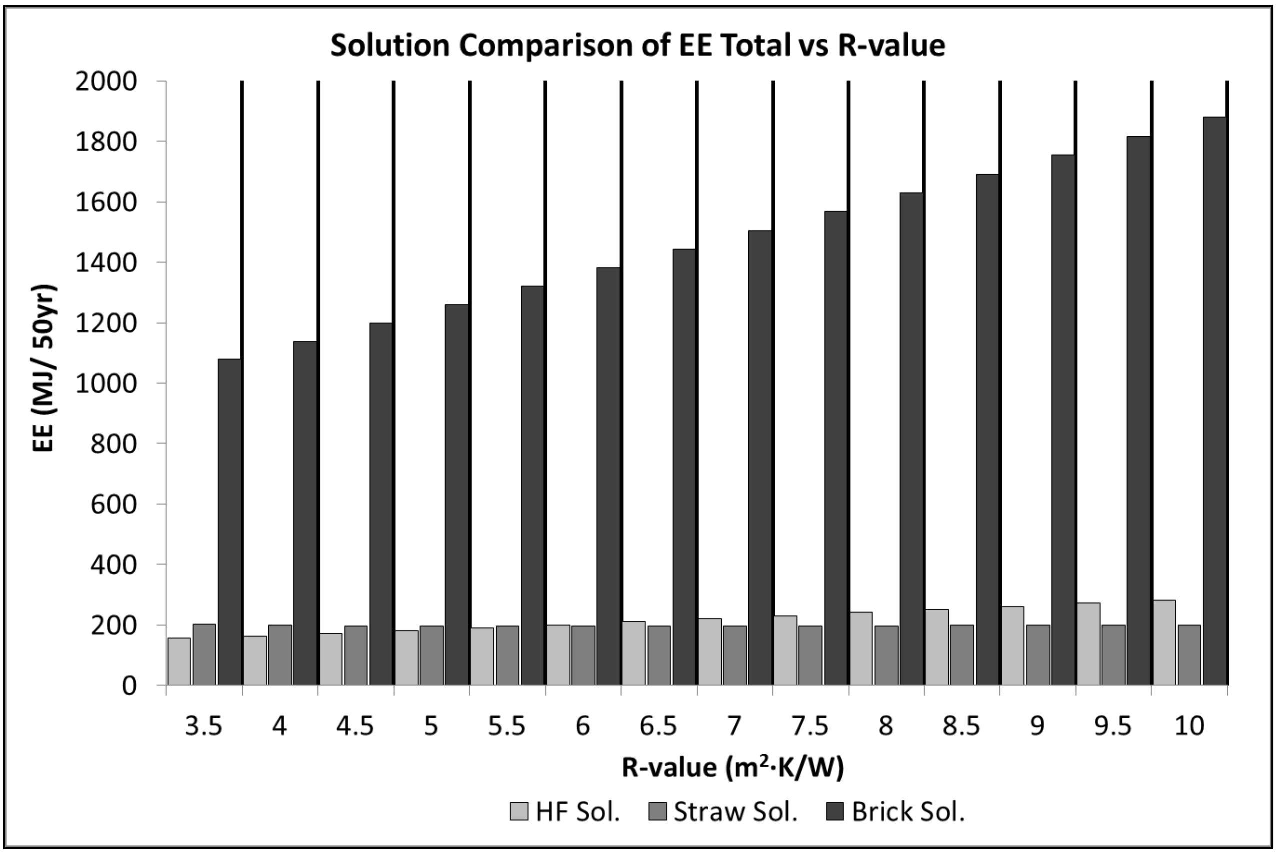


Figure 5.17 Solution Comparison of Total Embodied Energy vs R-value

From **Figures 5.16** and **5.17**, a difference in EL and EE total magnitude and function of R-value trend can be seen between the wall solutions. Since the same PV panels were used for all three solutions the difference in magnitude between the solutions EL and EE totals can easily be attributed to the different wall materials used. But explaining the difference in function trends is not as simple. Both the hemp/flax and straw solution EL functions of R-value exhibit a parabolic curve with an optimum R-value around 6.5 to 7.5 m^2K/W, while the brick solution indicates a hyperbolic curve. By only considering EL Total results, it cannot accurately be determined if the brick solution's EL function of R-value will remain hyperbolic or reach an optimum R-value and become parabolic outside the set R-value range. Additionally both the brick and hemp/flax solution EE functions of R-value indicate a linear trend, while the straw solution shows a parabolic curve. Again this difference cannot be explained by only considering the EE Total results.

In order to gain a better understanding of the trend differences each solution had their individual EL and EE Total functions of R-value analysed. Because the EL and EE Total functions' rate of change or slope is ultimately the deciding factor for what trends are produced this aspect was the focus of this analysis. The main two components that comprise the EL and EE Total results are the inputted wall materials and PV panels needed for the operating energy demand, which both have significantly different rates of change as the thermal resistance increases. In the next sections each solution's EL and EE Total results are individually broken down into inputted material and PV panel impact.

6 ANALYSIS & DISCUSSION

6.1 Solution Comparison Results

In order to determine why the different material solutions and PV panels all had varying rates of change, the equations of EL as a function of R-value or ***f(R)*** and the rate of change of this function or ***f'(R)*** were examined. The derivation of the general function formulas for the PV panel and material EL impact are presented in **Equations 6.1-6**.

In the original EL assessment the general equation for calculating the PV panel EL was a function of how many PV panels were being used, as shown in **Equation 6.1**. The total PV panel EL impact, ***f(n)***, was the summation of the number of required panels for operational energy demand, ***n***, multiplied by their direct and indirect EL per panel. Additionally the shorter 25 year lifespan of the panels themselves was accounted for by only dividing the PV panel impact by 25 instead of 50 years. But, since the actual footprint of the panels themselves will not be replaced this surface area, ***A***, did not need to be accounted for twice and was divided by 50 years. All of the variables are constants inputted with the chosen energy supply for the solution except for ***n***, which can be adjusted depending on the thermal performance of the solutions themselves. This equation was then converted into a function of R-value by substituting the shared ***n*** variable used in the heat loss and operational energy calculations, shown in **Equation 6.2**. The final resulting equation as a function of R-value is shown in **Equation 6.3**, where ***n*** is replaced by the product of the annual heat loss and surface area of wall divided by the product of R-value (***R***), coefficient of performance for the heat pump (***COP***), and power output of the PV panel (***P***).

General Equation for PV Panel EL as a Function of R-value

(6.1)

$$f(n)_{pv} = \left[(n)\left(EL_{\,Direct\,per\,panel} + EL_{Indirect\,per\,panel}\right)\left(\frac{2}{50}\right)\right] + \left[(n)\cdot(A)\cdot\left(\frac{1}{50}\right)\right]$$

Where:

$f(n)_{pv}$ = PV panel EL as a function of number of panels

$EL_{Direct\ per\ panel}$ = direct embodied land for every one PV panel

$EL_{Indirect\ per\ panel}$ = indirect embodied land for every one PV panel

n = number of PV panels being used

A = physical footprint of one PV panel

$$n = \frac{E}{P} = \frac{Q}{COP \cdot P} = \frac{\Delta T \cdot S \cdot 0.0036}{R \cdot COP \cdot P}$$

$$E = \frac{Q}{COP}\ ; Q = \frac{\Delta T \cdot S \cdot 0.0036}{R} \tag{6.2}$$

Where:

ΔT = total annual heat loss

S = surface area of wall element

R = thermal resistance

COP = coefficient of performance associated with the electricity to heat conversion equipment

P =electrical power output of one PV panel

$$f(R)_{pv} = \left[\left(\frac{\Delta T \cdot S \cdot 0.0036}{R \cdot COP \cdot P}\right)\left(EL_{\ Direct\ per\ panel} + EL_{Indirect\ per\ panel}\right)\left(\frac{2}{50}\right)\right] + \left[\left(\frac{\Delta T \cdot S \cdot 0.0036}{R \cdot COP \cdot P}\right) \cdot (A) \cdot \left(\frac{1}{50}\right)\right] \tag{6.3}$$

Where:

$f(R)_{pv}$ = PV panel EL as a function of R-value

In the original EL assessment the general equation for calculating the material EL impact was a function of how much of each material was being used or ***m***, which is shown in **Equation 6.4**. The total material impact equalled the summation of the changing insulation and wood frame as well as the constant materials all multiplied by their respective EL per kg. Since there was not enough information known about each material and assembly in each solution, the wood framing was considered to change in proportion to the insulation material, which was represented by the fraction, $\boldsymbol{m_w/m_i}$. This equation was converted into a function of R-value by substituting the shared $\boldsymbol{m}$ variable used in the thermal resistance calculations, shown in **Equation 6.5**. The final resulting equation as a function of R-value is shown in **Equation 6.6**, where $\boldsymbol{m}$ was replaced by the product of R-value of insulation ($\boldsymbol{R}$), surface area of wall ($\boldsymbol{S}$), thermal conductivity of insulation ($\boldsymbol{\lambda}$), and density of insulation ($\boldsymbol{\rho}$).

General Equation for Material EL as a Function of R-value

$$f(m)_{mat} = \left(\frac{1}{50}\right)\left[(m_i)\left(EL_{i\,per\,kg} + \frac{m_w}{m_i}\left(EL_{w\,per\,kg}\right)\right) + \sum\left(m_z \cdot EL_{z\,per\,kg}\right)\right] + A \qquad \textbf{(6.4)}$$

Where:

$f(m)_{mat}$ = material EL as a function of material mass

$EL_{i\ per\ kg}$ = embodied land per kg of adjusted insulation

$EL_{w\ per\ kg}$ = embodied land per kg of wood support frame

m_i = mass of insulation

m_w = mass of wood support frame

m_z = mass of other materials that remain constant

A = physical footprint of wall

$$\begin{gathered} m = S \cdot t \cdot \rho = R \cdot \lambda \cdot S \cdot \rho \\ t = R \cdot \lambda \\ A = 6(t_{wall}) = 6(t_i + k) = 6[(R_i \cdot \lambda_i) + k] \end{gathered} \qquad \textbf{(6.5)}$$

Where:

t = thickness

ρ = density

λ = thermal conductivity

k = constant thickness of other materials

$$\begin{aligned} f(R)_{mat} = \left(\frac{1}{50}\right)\Big[(R_i \cdot \lambda_i \cdot \rho_i \cdot S)\Big(EL_{i\,per\,kg} + \frac{m_w}{m_i}\left(EL_{w\,per\,kg}\right) \\ + \sum\left(m_z \cdot EL_{z\,per\,kg}\right)\Big)\Big] + 6[(R_i \cdot \lambda_i) + k] \end{aligned} \qquad \textbf{(6.6)}$$

Where:

$f(R)_{mat}$ = material EL as a function of R-value

By examining the resulting general EL functions it was determined that the most influential variables that differentiated each solution's material EL impact were the thermal conductivity, density, mass, and the embodied land per kg of the materials used. Additionally the most influential variables for the general PV panel EL function were the total annual heat loss, coefficient of performance for the heat pump used to convert the heat into electrical energy for the PV panels and the power output of the PV panels themselves.

Using **Equations 6.3** and **6.6** as the final derivations of the general equations for EL as a function of R-value for PV panels and materials, the specific equations for each solution were calculated in **Equations 6.7-14**. Since all of the solutions achieved the same R-values they also had the same PV panel impact, which is why there is only one specific PV panel EL equation shown in **Equation 6.8**.

Specific Equation for PV Panel EL as a Function of R-value

$$f(R)_{pv} = \left(\frac{75519K \cdot 18m^2 \cdot 0.0036\frac{MJ}{W}}{R \cdot 6 \cdot 432MJ}\right)\left[(4.97m^2yr + 4304.42m^2yr)\left(\frac{2}{50}\right) + 1\left(\frac{1}{50}\right)\right] \quad \textbf{(6.7)}$$

$$f(R)_{pv} = 325.48 \cdot R^{-1}\left[\frac{m^2}{50yr}\right] = 0.0325 \cdot R^{-1}\left[\frac{ha}{50yr}\right] \quad \textbf{(6.8)}$$

Specific Equation for Hemp/Flax Solution Material EL as a Function of R-value

$$f(R)_{mat} = \left(\frac{1}{50}\right)\left[\left(0.43R \cdot 0.039\frac{W}{mK} \cdot 30\frac{kg}{m^3} \cdot 18m^2\right)\left(6.57\frac{m^2yr}{kg} + 10.4\frac{m^2yr}{kg} + 7.93\left(1.99\frac{m^2yr}{kg}\right)\right) + 489.6kg\left(0.622\frac{m^2yr}{kg}\right)\right] + 6\left[\left(0.85R \cdot 0.039\frac{W}{mK}\right) + 0.034m\right] \quad \textbf{(6.9)}$$

$$EL_i = 6.07R + 6.30\left[\frac{m^2}{50yr}\right] = 6.07 \times 10^{-4}R + 6.30 \times 10^{-4}\left[\frac{ha}{50yr}\right] \quad \textbf{(6.10)}$$

Specific Equation for Straw Solution Material EL as a Function of R-value

$$\begin{aligned} f(R)_{mat} = \left(\frac{1}{50}\right)\Bigg[&\left(0.82R \cdot 0.06\frac{W}{mK} \cdot 112.5\frac{kg}{m^3} \cdot 18m^2\right)\left(2.5\frac{m^2yr}{kg}\right. \\ &\left.+ 0.11\left(1.99\frac{m^2yr}{kg}\right)\right) + 109.56kg\left(1.99\frac{m^2yr}{kg}\right) \\ &+ 942.84kg\left(7.07 \times 10^{-3}\frac{m^2yr}{kg}\right) + 28.83kg\left(0.0125\frac{m^2yr}{kg}\right) \\ &+ 0.01kg\left(0.192\frac{m^2yr}{kg}\right) + 0.01kg\left(0.23\frac{m^2yr}{kg}\right) \\ &+ 0.28kg\left(6130\frac{m^2yr}{kg}\right) + 270kg\left(3.29\frac{m^2yr}{kg}\right)\Bigg] \\ &+ 6\left[\left(0.82R \cdot 0.06\frac{W}{mK}\right) + 0.093m\right] \end{aligned} \quad \textbf{(6.11)}$$

$$f(R)_{mat} = 5.73R + 57.15\left[\frac{m^2}{50yr}\right] = 5.73 \times 10^{-4}R + 5.72 \times 10^{-3}\left[\frac{ha}{50yr}\right] \quad \textbf{(6.12)}$$

Specific Brick Solution Insulation EL vs R-value Equation

$$
\begin{aligned}
f(R)_{mat} = \left(\frac{1}{50}\right)\Bigg[&\left(0.96R \cdot 0.04\frac{W}{mK} \cdot 45\frac{kg}{m^3} \cdot 18m^2\right)\Bigg(0.498\frac{m^2yr}{kg} \\
&+ 1.87\left(1.99\frac{m^2yr}{kg}\right)\Bigg) + 92.6kg\left(40.8\frac{m^2yr}{kg}\right) \\
&+ 1829.48kg\left(6.94 \times 10^{-3}\frac{m^2yr}{kg}\right) + 457.37kg\left(7.07 \times 10^{-3}\frac{m^2yr}{kg}\right) \\
&+ 103.44kg\left(0.0125\frac{m^2yr}{kg}\right) + 605.07kg\left(0.0713\frac{m^2yr}{kg}\right) \\
&+ 648kg\left(0.622\frac{m^2yr}{kg}\right) + 2.52kg\left(0.192\frac{m^2yr}{kg}\right) \\
&+ 473.06kg\left(9.09 \times 10^{-4}\frac{m^2yr}{kg}\right) + 7.18kg\left(6130\frac{m^2yr}{kg}\right) \\
&+ 13.04kg\left(6130\frac{m^2yr}{kg}\right)\Bigg] + 6\left[\left(0.96R \cdot 0.04\frac{W}{mK}\right) + 0.17m\right]
\end{aligned}
\tag{6.13}
$$

$$
f(R)_{mat} = 2.84R + 2564.84\left[\frac{m^2}{50yr}\right] = 2.84 \times 10^{-4}R + 0.256\left[\frac{ha}{50yr}\right] \tag{6.14}
$$

It can be seen that all of the specific material impact equations are linear functions of R-value while the PV Panel impact equation is a non-linear function. By taking the derivative of **Equations 6.8, 6.10, 6.12** and **6.14** the rate of change or slope equations for EL as a function of R-value were determined. In order to find the optimum R-value for each solution where EL Total is the lowest and the material EL rate of change begins to outweigh the PV panel EL rate of change, the material EL rate of change equations were set equal to the PV panel EL rate of change equation and solved for R. The results of calculating these optimum R-values are presented in **Equations 6.15-17** and illustrated in **Figure 6.1**.

Hemp/Flax Solution Optimum EL R-value

$$
\begin{gathered}
f'(R)_{mat} = f'(R)_{pv} \\
6.07 \times 10^{-4} = 0.0326R^{-2} \\
R = \sqrt{\frac{0.0326}{6.07 \times 10^{-4}}} = 7.32
\end{gathered}
\tag{6.15}
$$

Straw Solution Optimum EL R-value

$$
\begin{gathered}
f'(R)_{mat} = f'(R)_{pv} \\
5.73 \times 10^{-4}R = 0.0326R^{-2} \\
R = \sqrt{\frac{0.0326}{5.73 \times 10^{-4}}} = 7.53
\end{gathered}
\tag{6.16}
$$

Brick Solution Optimum EL R-value

$$
\begin{gathered}
f'(R)_{mat} = f'(R)_{pv} \\
2.84 \times 10^{-4}R = 0.0326R^{-2} \\
R = \sqrt{\frac{0.0326}{2.84 \times 10^{-4}}} = 10.70
\end{gathered}
\tag{6.17}
$$

By presenting the results in the form of a line graph as opposed to a bar graph the trends between the PV panels and materials EL rate of change become more transparent. The EL rate of change for the brick solution insulation was much lower than the hemp/flax and straw solution, which resulted in its optimum EL being located outside the assessment's thermal resistance range and explains why the brick solution EL trend in **Figure 5.12** never overcame the rate of decreasing PV panels to form a full parabolic curve.

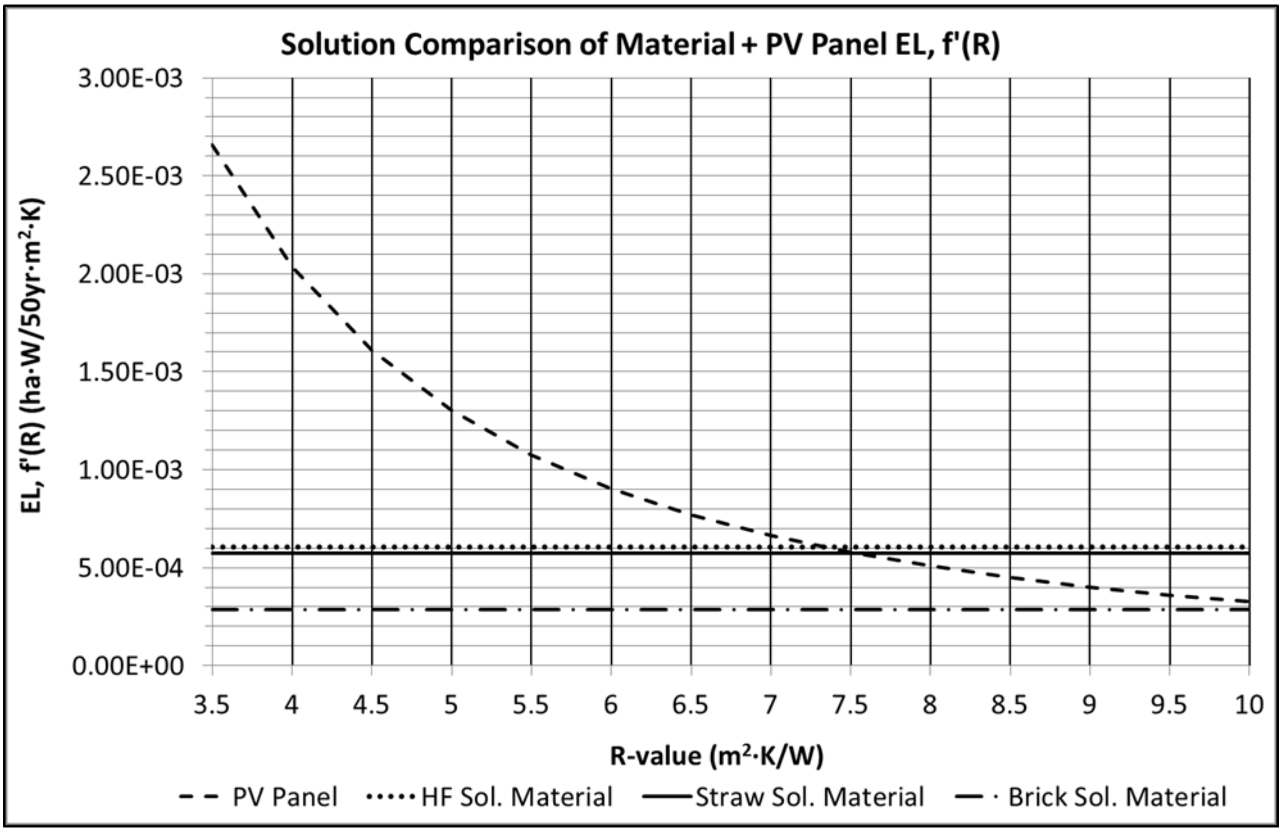


Figure 6.1 Solution Comparison of Material + PV Panel Embodied Land Rate of Change as a Function of R-value

Although the embodied energy results do not represent the full sustainability capacity limits of the facade solutions, it was still important to see if the difference in EE as a function of R-value trends could be explained. Using the same methods of explaining the previous EL functions, the specific solution's EE as a function of R-value were determined using **Equation 6.18** and **6.19**. Additionally the solution's rate of change functions or derivatives were also calculated to produce the optimum EE R-value results shown in **Figure 6.2**. The hemp/flax, straw and brick solutions had their optimum EE R-values at 2.26, 6.8, and 0.9 m^2·K/W respectively. It can be seen in **Figure 6.2** that the reason the straw solution had a slight parabolic curve in its total EE graph shown in **Figure 5.9** was because its material had an EE rate of change much lower than the other two solutions. This resulted in the PV panel EE rate of change to outweigh the material EE rate of change at the lower range of R-values.

General Equation for PV Panel EE as a Function of R-value

(6.18)

$$f(R)_{pv} = \left(\frac{\Delta T \cdot S \cdot 0.0036}{R \cdot COP \cdot P}\right)\left(EE_{\ per\ panel}\right)\left(\frac{2}{50}\right)$$

Where:

$f(R)_{pv}$ = PV panel EE as a function of R-value

General Equation for Material EE as a Function of R-value

$$f(R)_{mat} = \left(\frac{1}{50}\right)\left[(R_i \cdot \lambda_i \cdot \rho_i \cdot S)\left(EE_{i\,per\,kg} + \frac{m_w}{m_i}(EE_{w\,per\,kg}) + \sum(m_z \cdot EE_{z\,per\,kg})\right)\right] \quad \textbf{(6.19)}$$

Where:

$f(R)_{mat}$ = material EE as a function of R-value

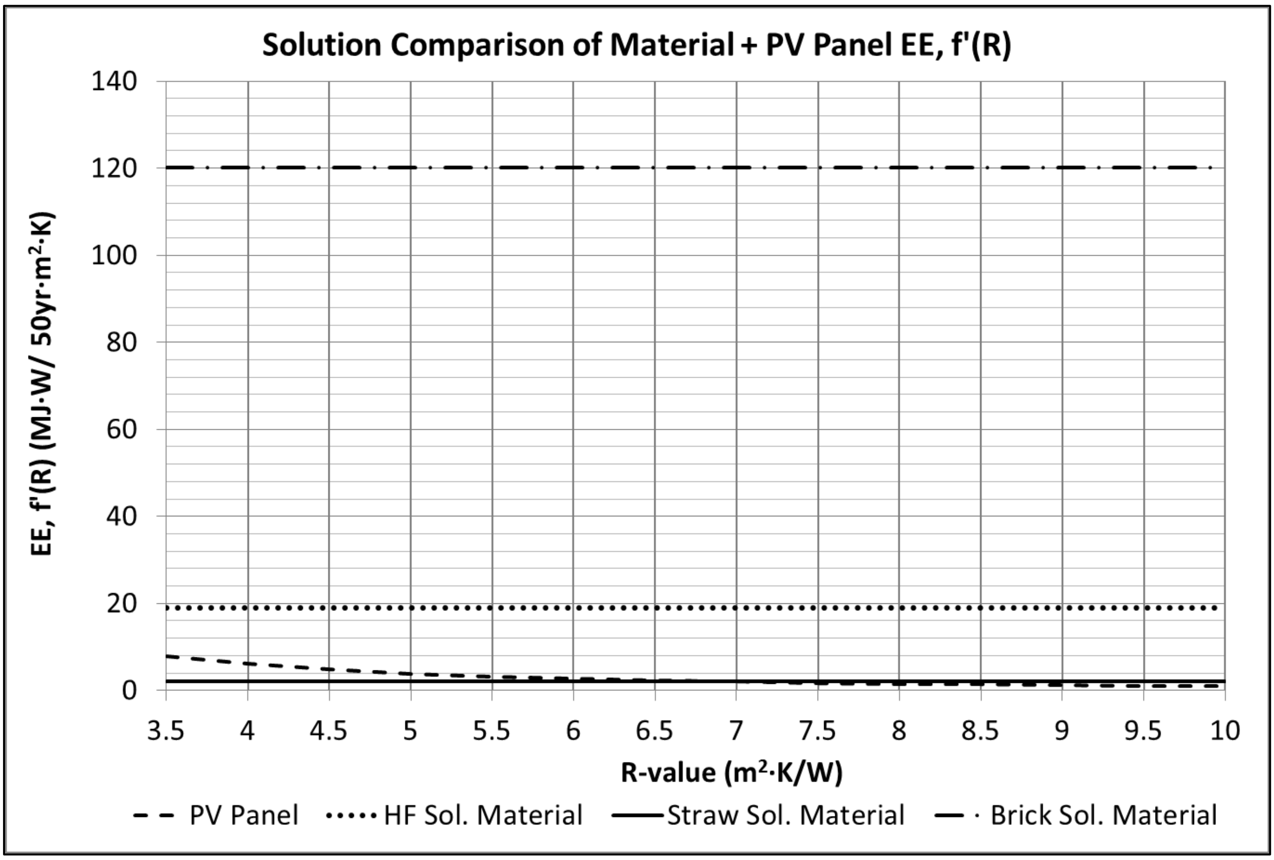


Figure 6.2 Solution Comparison of Material + PV Panel Embodied Energy Rate of Change as a Function of R-value

After analyzing how the three different envelope wall solutions compared using MAXergy's perspective of sustainability, the results have shown that the brick wall solution created a significantly larger embodied land burden on the closed system versus the hemp/flax and straw solutions. These results help justify the argument that biotic regrowable material solutions are more sustainable than more processed contemporary material solutions. Although the biotic regrowable materials tended to have a larger EL Direct due to their production footprint, this was significantly less than the EL Indirect needed to compensate for the embodied energy and return energy of the slower regenerating and more processed materials such the cement and steel included in the brick solution.

Additionally, the calculated EL rate of change functions of R-value indicated that in order for building solutions to have the most sustainable design, they must find a relative optimized balance between the amount of materials being used and the amount of energy being supplied. This means that the increase in insulation material and its benefit of reducing energy demand may become irrelevant and wasteful at an optimum point but it is not guaranteed as the brick solution results demonstrate. This optimum point is where the rate of embodied land increase for materials becomes equal to or greater than the rate of embodied land decrease for PV panels as the wall solutions achieve higher thermal resistance values. But even though the lowest EL total for the brick solution is at a very high R-value this does not mean it was the most sustainable choice when comparing its starting EL value to the hemp/flax and straw solutions

6.2 Accuracy and Sensitivity of Results

Besides the initial assumptions on the lifespan and surface area of the envelope wall solutions, there are not many other instances where non-objective decisions were made. These initial characteristics of the envelope wall elements helped establish the theoretical system boundaries necessary for comparing each solution's ability to achieve the assumed closed loop or net-0 cycle for material and energy.

6.2.1 Primary Embodied Energy vs Final Embodied Energy

The most significant factor contributing to the potential depreciation of accuracy in this assessment was the original MAXergy embodied energy values for materials that were obtained from the ICE database. Because these embodied energy values were calculated using the summation of primary energy sources, which is the same technique used by common life cycle inventory databases such as sima pro and eco invent, the compensating PV panel electricity output is not realistically equivalent to these values. Since primary energy can come from many different sources such as fossil fuels and heat, their respective embodied energy totals need to be converted into final electrical energy, which requires energy losses. Therefore final embodied energy of the materials should be considered for the PV panel energy demand which will reduce the actual embodied energy being considered and could potentially shift the optimum EL point to a higher R-value.

Additionally the ICE embodied energy values consider average transportation energy for each material, which contradicts the ideals of MAXergy. Since MAXergy assumes the ideal sustainable solution should be designed within its local environmental limits and its materials and energy should be produced on site, the need for transporting materials large distances is irrelevant and should not be considered in the sustainability assessment.

6.2.2 Theoretical Embodied Land Functions vs Simulation Results

As for the calculations of EL optimum R-values, it was found that the percent error between the theoretical equations and the actual simulated solution results was 4.4% for the hemp/flax solution, 2.7% for the straw solution, and 0.03% for the brick solution. These errors come from general values being rounded and also the changing support wood frame EL impact calculations being simplified to a proportionality of the insulation and its R-value in each solution. Both of these can be reduced by obtaining the exact R-values of all the materials in the final wall assembly products from each solution's original thermal performance testing. For this paper that information was not available, but the resulting percent error for all the solutions was under 5% and relatively small.

6.2.3 Change in Materials and Climate

So far this assessment has given insight on the sustainability comparisons between common hemp/flax, strawbale, and brick veneer envelope wall solutions in the Netherlands, but how are these results affected with different materials, different scales of elements being assessed and different climate regions? The relation between EL and material type and mass will carry over into other building solutions. For example, since concrete wall designs typically require cement and steel to be constructed, its EL Total will be much greater than a solution that would use mainly bamboo, due to similar embodied energy and return energy differences. Additionally, the more materials being considered in an assessment increases the surface area being considered for heat loss, which increases the material EL rate of change. As far as optimizing the materials themselves for a selected solution, apart from changing their quantities there is not much else that can be done by building designers to significantly lower there embodied land properties.

In order to consider different climate regions, the change in amount of energy demand needed to compensate for heat loss was explored. **Figures 6.3** and **6.4** illustrates the EL and EE rate of change per R-value when considering annual Portugal (PT) weather data. The results from **Figures 6.3** and **6.4** show a shift in where the EL and EE Total minimums for each solution are located. Instead of the EL optimal points occurring at an

R-value of 7.32, 7.53, and 10.7 $m^2 \cdot K/W$, in a Portuguese climate the hemp/flax and straw solutions had their lowest EL Total at an R-value of 5.5 and 5.7 $m^2 \cdot K/W$ respectively, while the brick solution had its lowest EL Total at an R-value of 8.1 $m^2 \cdot K/W$. Instead of the EE optimal points occurring at 2.26, 6.8, and 0.9 $m^2 \cdot K/W$, the Portuguese climate data shifted the hemp/flax, straw and brick solutions lowest EE Totals to 1.70, 5.12 and 0.68 $m^2 \cdot K/W$ respectively. This shift to the left of the optimum R-values is logical since there was significantly less heat loss from the warmer climate in Portugal which led to less required energy demand and a reduced PV Panel impact. This change is drastic enough to conclude that the assessment is very sensitive to what climate is being considered.

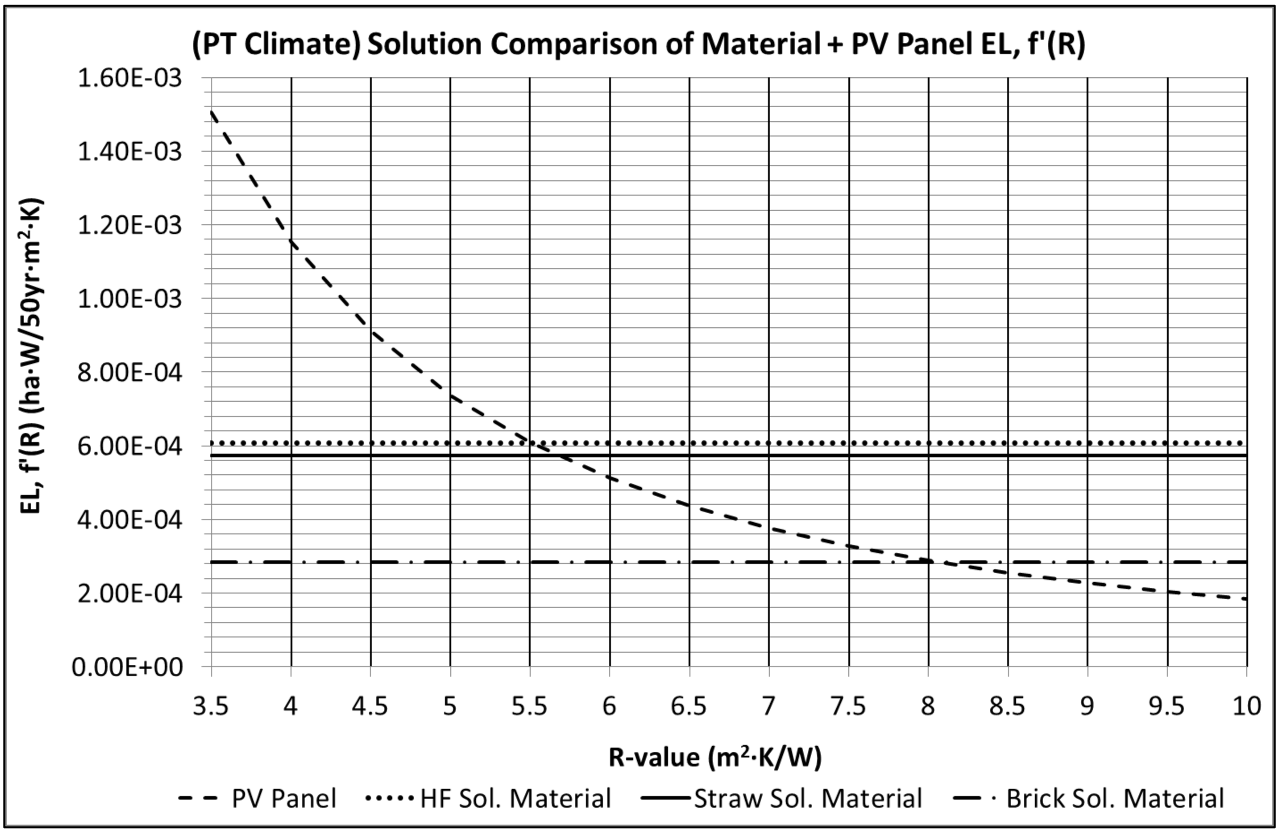


Figure 6.3 Solution Comparison of Material + PV Panel Embodied Land Rate of Change as a Function of R-value (PT Climate)

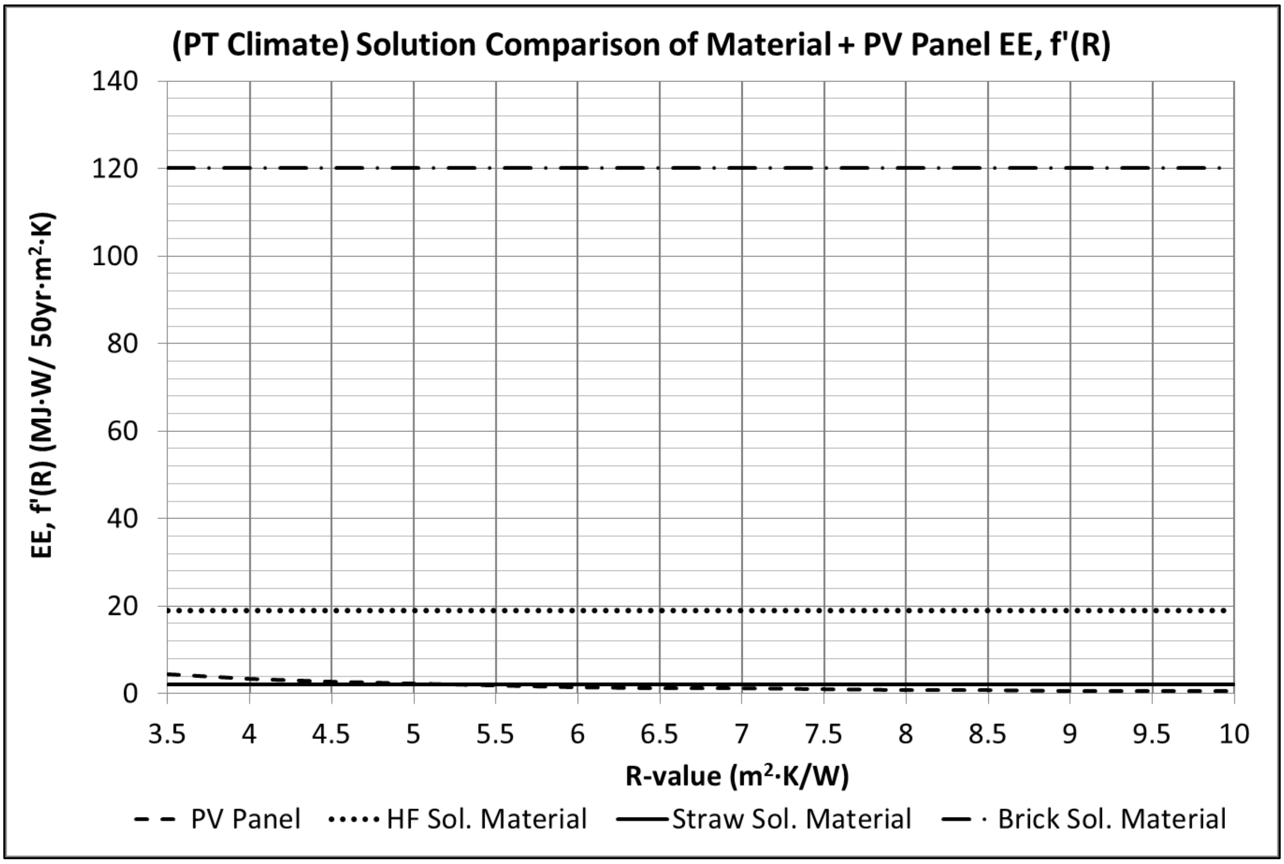


Figure 6.4 Solution Comparison of Material + PV Panel Embodied Energy Rate of Change as a Function of R-value (PT Climate)

6.2.4 Change in Equipment

The final sensitive aspects of the results are the power output of the PV Panels and coefficient of performance or COP assumed for the electric heat pump being considered for the conversion of the heat loss to electrical energy. Since both factors were located in the denominator of the coefficient for EL rate of change and would affect the results in the same manner only the COP was analysed here. The original assessment assumed the best possible COP of 6 from the source given, but **Figures 6.5 and 6.6** showed a shift to the right for the EL and EE optimum R-values using the worst case scenario of a COP of 3. The results for the hemp/flax, straw, and brick solutions showed EL optimum R-values of 10.36, 10.66, and 15.13 m^2·K/W and EE optimum R-values of 3.20, 9.61, and 1.27 m^2·K/W respectively. As well as the climate zone, changing the COP also produces significant enough differences to conclude that it is a very sensitive aspect for the assessment and that the type of equipment used is just as important, if not more, than the amount of insulation used.

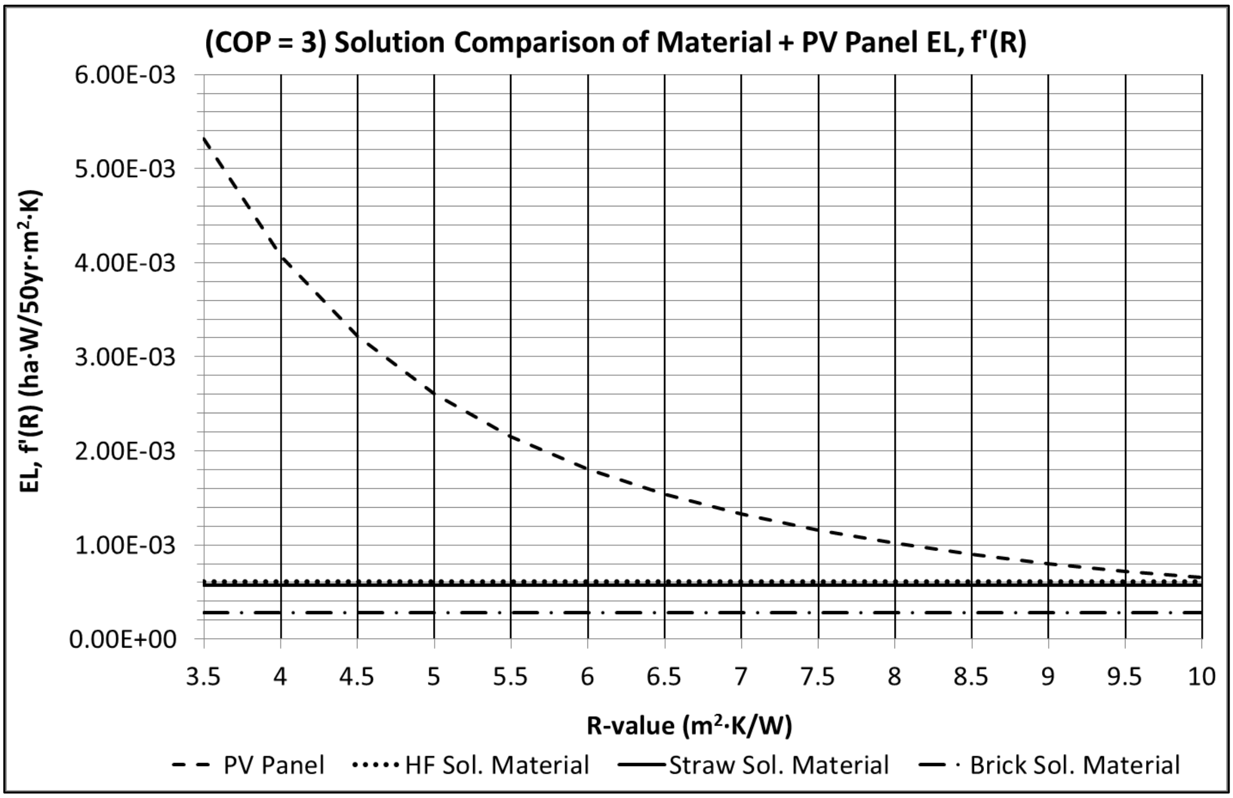


Figure 6.5 Solution Comparison of Material + PV Panel Embodied Land Rate of Change as a Function of R-value (COP = 3)

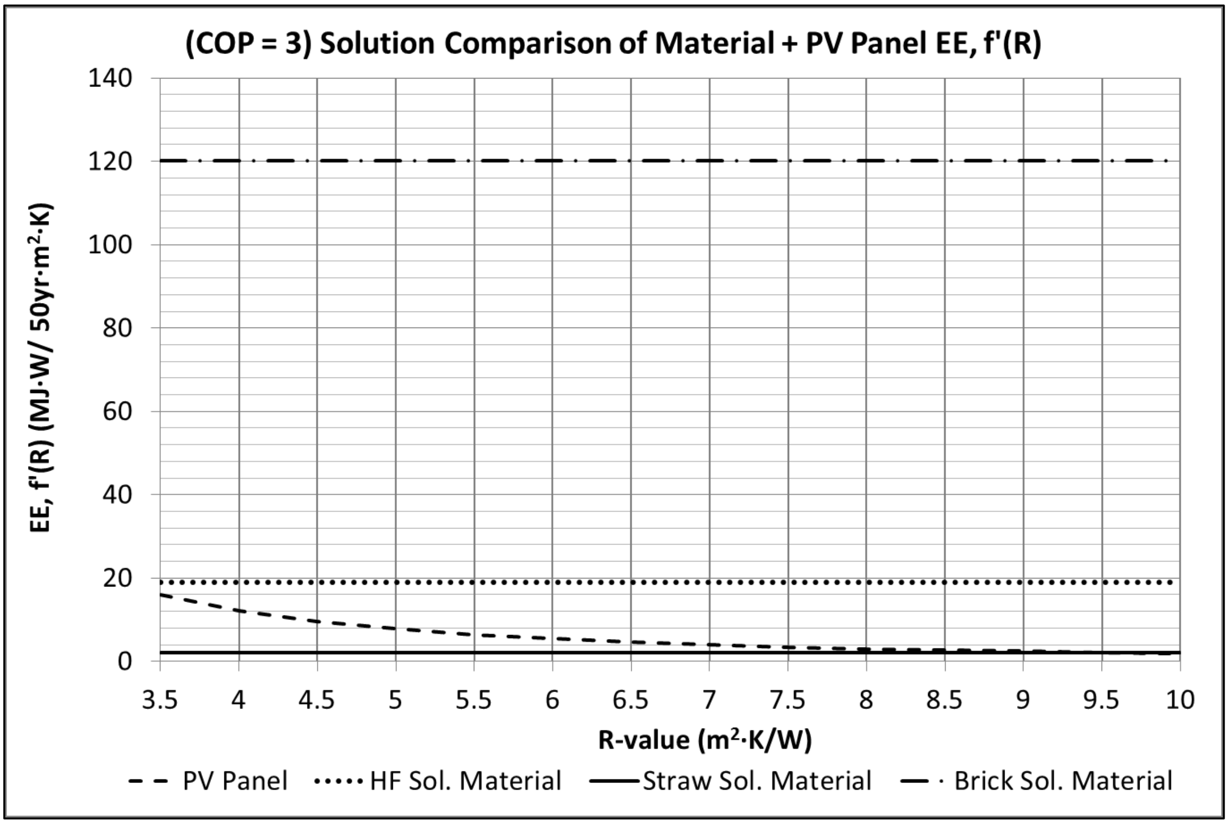


Figure 6.6 Solution Comparison of Material + PV Panel Embodied Energy Rate of Change as a Function of R-value (COP = 3)

6.3 Future Development

For future development of MAXergy and assessments like the one conducted for this paper, other improvements can be made to the versatility and functionality of the EL Tool. The EL tool has already been adapted to the English language for this research but it could always benefit from being translated into other languages and become more functional internationally.

The material database should continue to be expanded to include more materials and more accurate data sources for embodied energy other than ICE. In order for this assessment to provide the highest quality of accurate and objective results, the production, manufacturing, and installation EE values for all materials should be obtained from consistently updated sources that record practical final embodied energy data. This is difficult to find due to many agricultural practitioners and companies that handle the manufacturing of materials not making easily available the amount of energy consumed during their respective processes as well as the majority of life cycle assessments only considering primary embodied energy or being unclear with how their embodied energy values were calculated. Additional sources should also be found in order to acquire recycling data on existing materials being considered for the MAXergy assessment. Currently this type of data is very segregated between individual companies and typically doesn’t give a full record of a products history.

The energy supply database currently only includes PV panels and their material composition. This leaves room for more types of energy supply to be explored such as hydro, biofuel, wind, and geothermal. Other than that, the format and design of how the actual tool itself works could be made more intuitive. This would allow both experienced and inexperienced sustainable solution designers to more easily work with the tool.

Finally in order to improve the practicality of the MAXergy analysis process the general equations for material and PV panel EL as a function of R-value derived in this paper should be further developed. In order to provide a more realistic representation of embodied land more complicated energy simulations should be made to determine factors such as heat gain due to radiation and the time lag of peak heating hours for calculating energy demand impact and more absolute material properties should be used to determine the material impact.

7 CONCLUSION

In an industry focused on achieving 0-energy and closed cycle building solutions, the MAXergy methodology can be useful for determining the most sustainable materials and designs to use. The sustainability assessment conducted for this paper produced results that support the use of regrowable biotic materials over more conventional materials being used in the industry today. On average the brick facade solution was found to have significantly more embodied land than the straw and hemp/flax solutions. Although the solutions were adapted to a theoretical situation and absolute values were not the main focus, these results can help inform building designers when they are making choices on what materials to use and the EL Tool can be a platform for determining if the benefits of optimizing contemporary solutions are worth it. For example, concrete structures are now being modified to include fiber reinforcement to improve durability and cost effectiveness, but will these aspects be able to reduce its overall embodied land burden?

There is currently interest in the building industry for passive building designs and achieving net zero energy. Because the results have shown that only considering EE does not provide a complete picture of a solution's sustainable potential within its system capacity both the EL and EE functions of R-value derived in this paper can provide building designers with a better idea of how passive to make a building solution before the amount of materials becomes wasteful. Since this paper's assessment focused on only facade elements, the derived EL function equations can be especially useful for the participants of the More-Connect project who are developing prefab renovation solutions for existing building facades. Buildings will typically need to rely on some energy source for heating and cooling, but this can still be brought down to net 0 energy if renewable sources are used such as solar radiation.

In order for MAXergy assessments to be integrated into the existing system of how the building industry operates, it can be conducted separately but also in parallel with assessments that consider more common sustainability indicators such as economic costs, aesthetics, global warming potential, carbon dioxide emissions, etc. This would provide a more complete understanding of how a product's design would be affecting shorter term impacts. Although, ultimately the final deciding factor should be the physical realistic unit of embodied land, which represents how far away a product is from the ideal sustainable solution that satisfies basic human survival needs.

With continued research on renewable energy supply options, final EE values, and the optimization of how to balance the amount of energy supply and materials being used for thermal performance, the EL Tool will become a more useful educational platform for building designers, policymakers, and building owners in the near future. Also by expanding MAXergy's resource management ideals to water and food, more realistic sustainable solutions could be developed and it would encourage the building industry to cooperate with other industries such as agriculture and forestry. This cooperation would allow for a more collective approach to designing sustainable solutions and enhancing humanity's rate of progression towards creating a more sustainable society.

REFERENCES

ASHRAE 2013. Standard 55 - Thermal Environmental Conditions for Human Occupancy.

Baumit, 2015, Baumit Renders & Plasters, Baumit UK Ltd, Birmingham, England.

Bouwbesluit, Dutch Ministry of the Interior and Kingdom Relations, 2012,

Brundtland, G. H., World Commission on Environment and Development, 1987, Our Common Future, Oxford.

Carson, R. 1962. Silent Spring, Cambridge, Mass., Boston: Houghton Mifflin.

CEN. 2005. Overview of CEN/TC 350 [Online]. The European Committee for Standarization Available: http://portailgroupe.afnor.fr/public_espacenormalisation/centc350/index.html [Accessed November 3, 2014].

Cooper, J. S. & Fava, J. A. 2006, "Life-cycle Assessment Practitioner Survey: Summary of Results", Journal of Industrial Ecology, 10, 12-14, 10.1162/jiec.2006.10.4.12.

Development and Advanced Prefabrication of Innovative, Multifunctional Building Envelope Elements for Modular Retrofitting and Smart Connections, European Comission, 2014,

DHPA. 2013. Rendementen [Online]. Available: http://www.dhpa-online.nl/rendementen/ [Accessed February 25, 2015].

District of Tomorrow Phase Document MAXergy: Final Design > Work Preparation. 2013.

Dupont. 2015. Tyvek Supro [Online]. Available: http://www.dupont.co.uk/products-and-services/construction-materials/tyvek-building-envelope/brands/tyvek-breather-membrane/products/tyvek-supro-water-resistant-membrane.html [Accessed February 9, 2015].

EC, 2014 a, Communication From The Commision To The European Parliament, The Council, The European Economic And Social Committee And The Committee Of The Regions On Resource Efficiency Opportunities In The Building Sector,

EC. 2014 b. Europe 2020 Targets [Online]. Available: http://ec.europa.eu/europe2020 [Accessed October 10, 2014].

ECEEE. 2010. EPBD Recast (Directive 2010/31/EU) [Online]. European Council for an Energy Efficient Economy. Available: http://www.eceee.org/policy-areas/buildings/EPBD_Recast [Accessed November 7, 2014].

Ecococon. 2015. Straw Panels [Online]. Available: http://www.ecococon.lt/english/straw-panels/ [Accessed February 8, 2015].

Ehrlich, P. R. 1968. The Population Bomb, Sierra Club-Ballantine Book, New York, Ballantine Books.

Endicott, 2015, Brick Construction Details, Endicott, Fairbury, Nebraska.

González, A. D. 2013, "Energy and carbon embodied in straw and clay wall blocks produced locally in the Andean Patagonia", Energy and Building, 70, 15-22, 10.1016/j.enbuild.2013.11.003.

Haagen, T. 2015. Energieneutrale renovatie: komt dat zien!? Een energieneutraal renovatieconcept voor eigenaar-bewoners van vrijstaande jaren dertig woningen in Nederland. Master Thesis, University of Technology Eindhoven, Netherlands.

IEA-UNDP, United Nations Development Program, 2013, Modernising Building Energy Codes, OECD/IEA, Paris.

IEA. 2011. Technology Roadmaps [Online]. International Energy Agency. Available: http://www.iea.org/roadmaps/ [Accessed November 8, 2014].

IEA, International Energy Agency, 2013, Transition to Sustainable Buildings: Strategies and Opportunities to 2050, OECD/IEA, Paris.

ISO 2005. Standard 7730 - Ergonomics of the thermal environment – Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria.

Isofloc. 2015. Product isofloc LM [Online]. Available: http://isofloc.com/assets/Produkte/Zellulosefasern/20140410-isofloc-LM-BUeT-en-mail.pdf [Accessed February 2015].

Lecouls, H. 1999, "ISO 14043: Environmental Management: Life Cycle Assessment: Life Cycle Interpretation", International Journal of Life Cycle Assessment, 4, 245,

NRC 1999. Our Common Journey: A Transition Toward Sustainability, Washington, DC, The National Academies Press.

Owen, R. L., Amor, R., Dickinson, J., Prins, M. & Kiviniemi, A. 2013. CIB Integrated Design & Delivery Solutions (IDDS) Research Roadmap, International Council for Research and Innovation in Building and Construction

Pryshlakivskya, J. & Searcy, C. 2013, "Fifteen years of ISO 14040: a review", Journal of Cleaner Production, 57, 115-123, 10.1016/j.jclepro.2013.05.038.

Ritzen, M., Meijden, B. v., Rovers, R., Vroon, Z. & Geurts, C. 2013, "Comparison and development of sustainable office facade renovation solutions in the Netherlands", Journal of Facade Design and Engineering 1, 53-71, 10.3233/FDE-130005.

Rovers, R., 2012, Evaluation of 0-materials house design, Research Institute Built environment of Tomorrow, Zuyd University Heerlen, Netherlands.

Rovers, R. 2013a. MAXergy: The Embodied Land Indicator: Background and Substantiation. Zuyd University, Netherlands.

Rovers, R., 2013b, Reducing energy demand – or producing more energy? The role and impact of materials in zero or near-zero energy building & renovation, RiBuilT, Heerlen, Netherlands.

SBSC. 2014. The Distrit of Tomorrow [Online]. Available: http://www.sustainablebuilding.info/districtoftomorrow/ [Accessed October 15, 2014].

Schenck, R. & Lalonde, S., Institute for Environmental Research & Education, 2013, Status and Opportunities to Support Product Category Rules in the U.S., National Institute of Standards and Technology, U.S. Department of Commerce.

SIGA, 2014, Product data sheet: SIGA - Majcoat SOB / Majcoat, SIGA,

Sodagara, B., Raib, D., Jonesc, B., Wihanc, J. & Fieldsond, R. 2011, "The carbon-reduction potential of straw-bale housing", Building Research & Information, 39**,** 51-65,

Solland Solar Cells [Online]. 2015. Pufin Power. Available: http://www.pufinpower.com/sito/sollandsolarcells/ [Accessed October 5, 2014].

SPSC, 2013, Wooden frame external panels with insulation straw core National technical assessment NTI-01-061:2013 State Enterprise Construction Products Certification Center,

TNS. 2013. Sustainability [Online]. The Natural Step. Available: http://www.naturalstep.org/en/the-system-conditions [Accessed October 2, 2014].

TRNSYS. 2015. Available: http://www.trnsys.com/ [Accessed January 20, 2015].

UN, United Nations, 1992, Rio Declaration on Environment and Development, Rio de Janeiro, Brazil.

UN. 2014 a. Millennium Development Goals and Beyond 2015 [Online]. Available: http://www.un.org/millenniumgoals/ [Accessed September 17, 2014].

UN. 2014 b. Sustainable Development Goals [Online]. Sustainable Development Knowledge Platform. Available: http://sustainabledevelopment.un.org/?menu=1300 [Accessed Septmeber 18, 2014].

Voorbeeldwoningen 2011 Bestaande bouw, 2011, Agentschap NL, Sittard, Netherlands.

WBCSD. 2014. Cement Sustainability Initiative: Sustainability With Concrete [Online]. Available: http://www.wbcsdcement.org/index.php/key-issues/sustainability-with-concrete [Accessed October 20, 2014].

WGBC. 2014. Nearly Zero-Energy Buildings [Online]. World GreenBuilding Council. Available: http://www.worldgbc.org/regions/europe/policy/nearly-zero-energy-buildings/ [Accessed October 5, 2014].

Wookey, R., Bone, A., Carmichael, C. & Crossley, A., Public Health England, 2014, Minimum home temperature thresholds for health in winter – A systematic literature review, Wellington House, London.

WWF. 2003. The 10 Principles of One Planet Living [Online]. World Wide Fund for Nature. Available: http://wwf.panda.org/what_we_do/how_we_work/conservation/one_planet_living/about_opl/principles/ [Accessed November 3, 2014].

APPENDIX

ISO 14040:1997		Altered?	Degree	ISO 14040:2006	
Boundary	Allocation	✓	Minimal	Boundary	Allocation
	Functional unit	✓	Minimal		Functional unit
	Product system	✓	Minimal		Product system
	System boundary	✓	Significant		System boundary
	Unit process	✓	Significant		Unit process
Material	Ancillary input	✓	Minimal	Material	Ancillary input
	Co-product	✓	Minimal		Co-product
	Elementary flow	×			Elementary flow
	Energy flow	×			Energy flow
	Environmental aspect	×			Environmental aspect
	Environmental mechanism	×			Environmental mechanism
	Feedstock energy	✓	Minimal		Feedstock energy
	Input	✓	Minimal		Input
	Intermediate flow	✓	Minimal		Intermediate flow
	Intermediate product	✓	Minimal		Intermediate product
	Life cycle	×			Life cycle
	Output	✓	Minimal		Output
	Process energy	✓	Minimal		Process energy
	Raw material	×			Raw material
	Reference flow	✓	Minimal		Reference flow
	Waste	✓	Minimal		Waste
Method	Category endpoint	✓	Minimal	Method	Category endpoint
	Characterization factor	✓	Minimal		Characterization factor
	Comparative assertion	×			Comparative assertion
	Completeness check	✓	Minimal		Completeness check
	Consistency check	✓	Minimal		Consistency check
	Data quality	✓	Minimal		Data quality
	Evaluation	✓	Minimal		Evaluation
	Impact category	×			Impact category
	Impact category indicator	×			Impact category indicator
	Life Cycle Assessment	×			Life Cycle Assessment
	Life Cycle Impact Assessment	✓	Minimal		Life Cycle Impact Assessment
	Life Cycle Interpretation	✓	Minimal		Life Cycle Interpretation
	Life Cycle Inventory analysis	✓	Minimal		Life Cycle Inventory analysis
	Life Cycle Inventory analysis result	✓	Minimal		Life Cycle Inventory analysis result
	Sensitivity analysis	✓	Minimal		Sensitivity analysis
	Sensitivity check	×			Sensitivity check
	Transparency	×			Transparency
	Uncertainty analysis	✓	Minimal		Uncertainty analysis
Misc.	Interested party	×		Misc.	Interested party
Removed	Final product			Added	Critical review
	Fugitive emission				Cut-off criteria
	Practitioner				Process
					Product
					Product flow
					Releases

Figure A.1 New 14040 Standard Changes (Pryshlakivskya and Searcy, 2013)

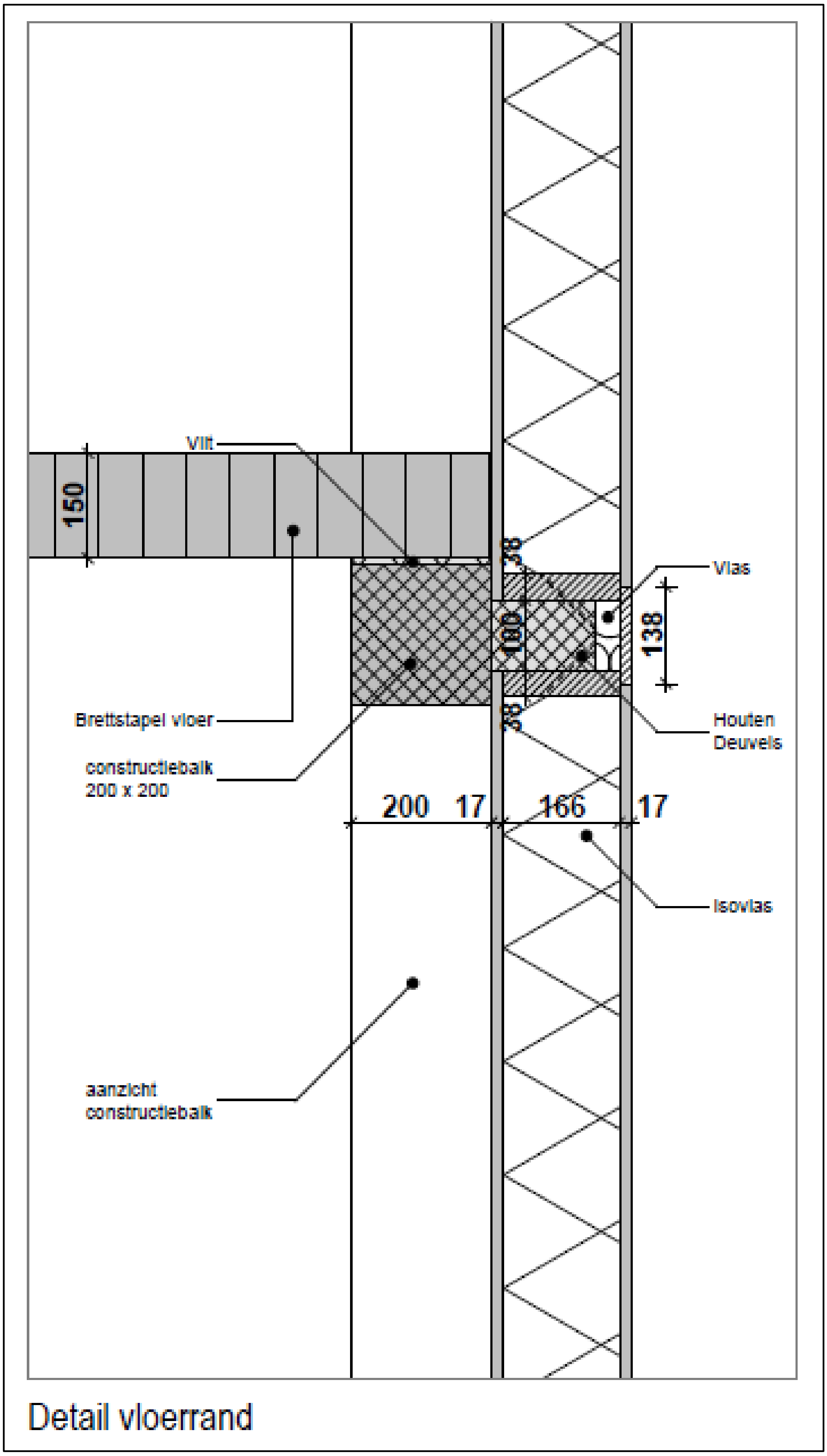


Figure A.2 Hemp/Flax Solution Cross Section Detail (*District of Tomorrow Phase Document MAXergy: Final Design > Work Preparation*, 2013)

Figure A.3 Hemp/Flax Solution Isometric View (*District of Tomorrow Phase Document MAXergy: Final Design > Work Preparation*, 2013)

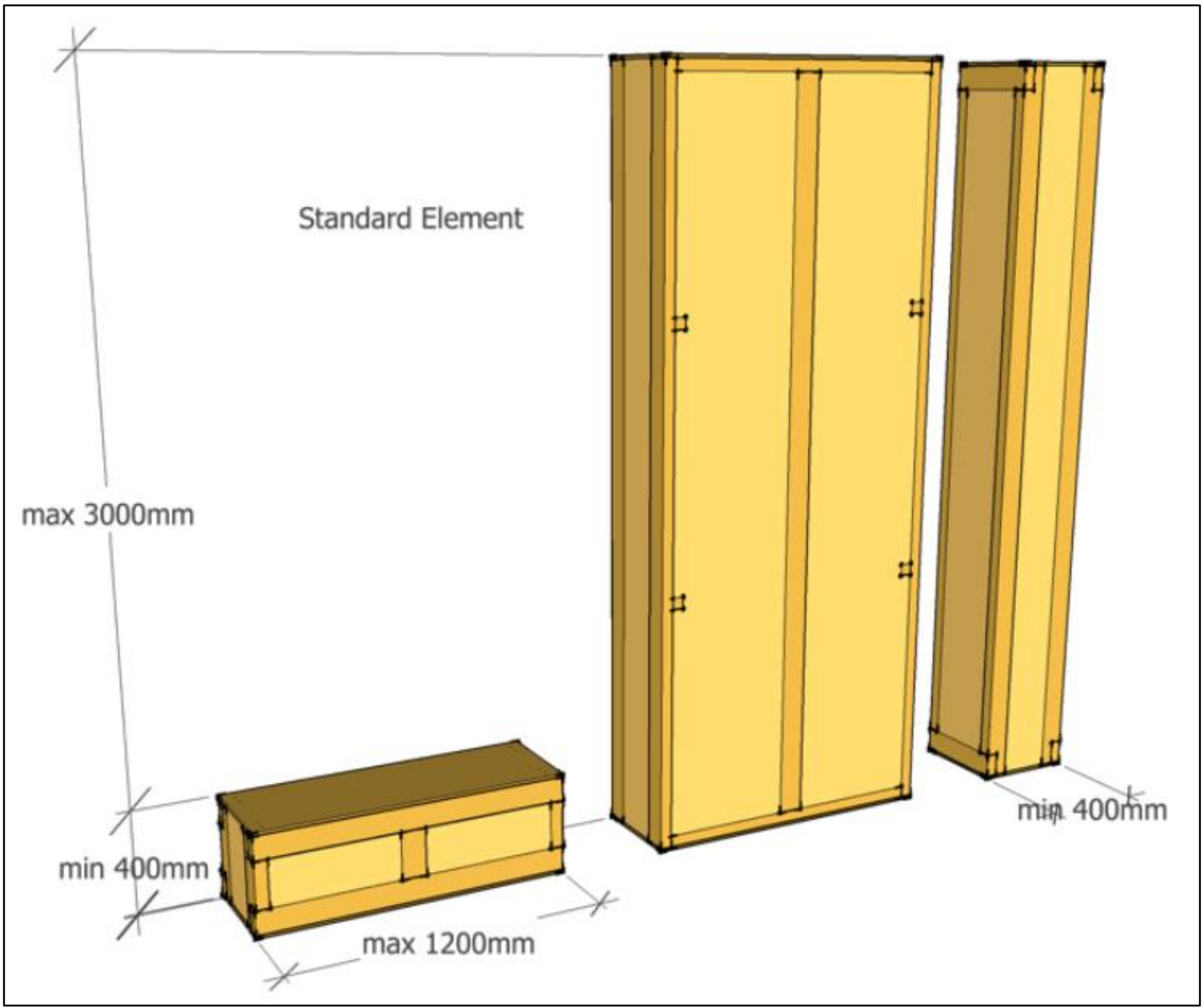


Figure A.4 Straw Solution Standard Prefab Panel Element Dimensions (Ecococon, 2015)

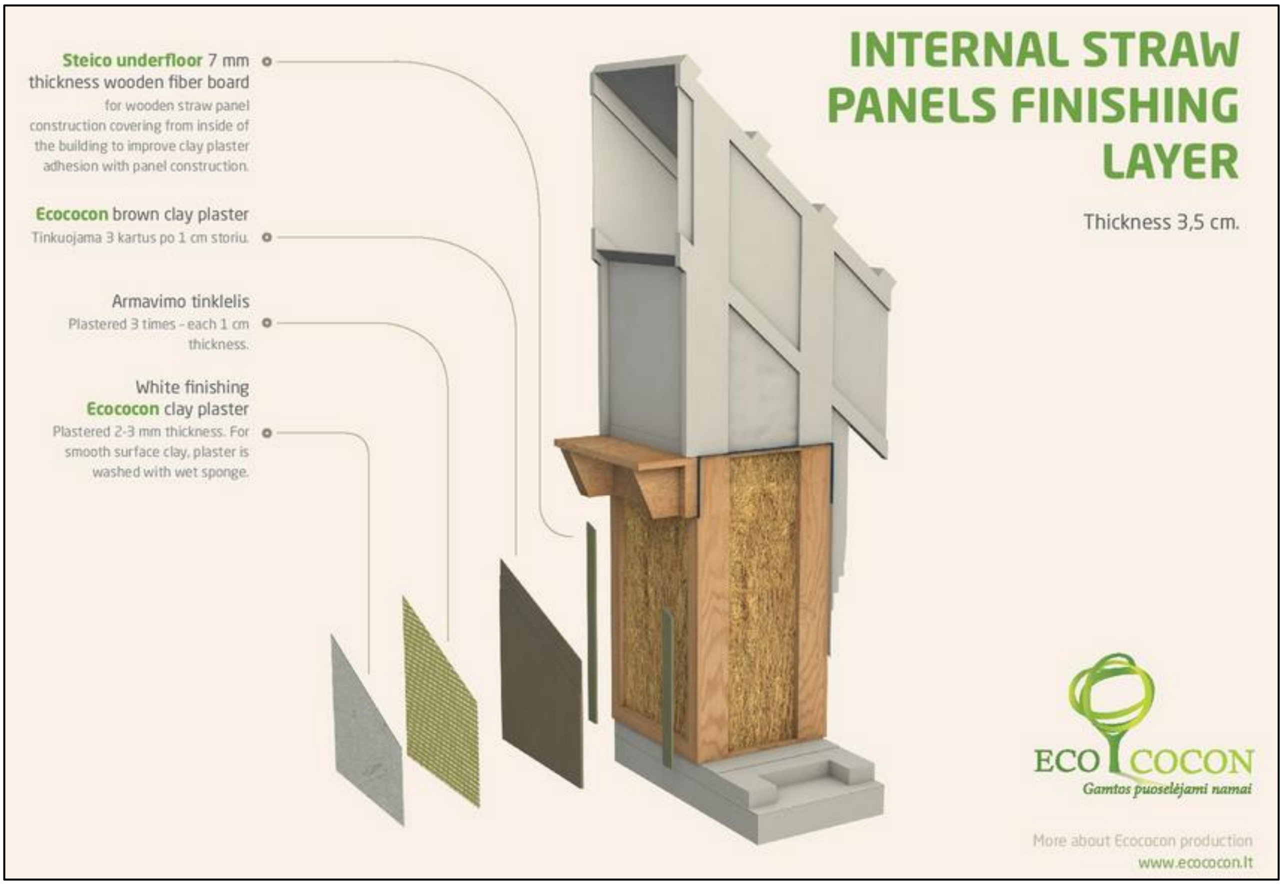


Figure A.5 Straw Solution Interior Finishing Layer Details (Ecococon, 2015)

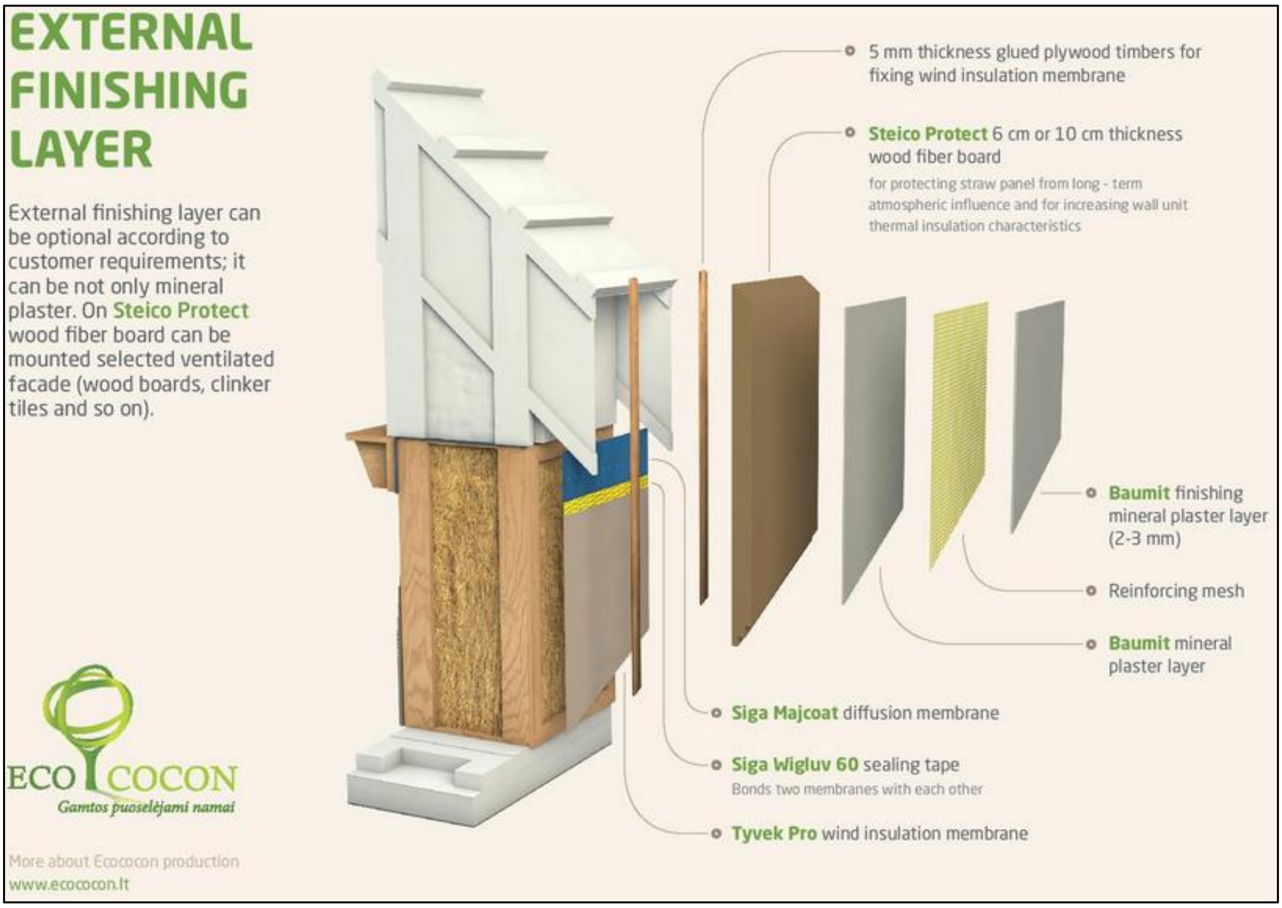


Figure A.6 Straw Solution Exterior Finishing Layer Details (Ecococon, 2015)

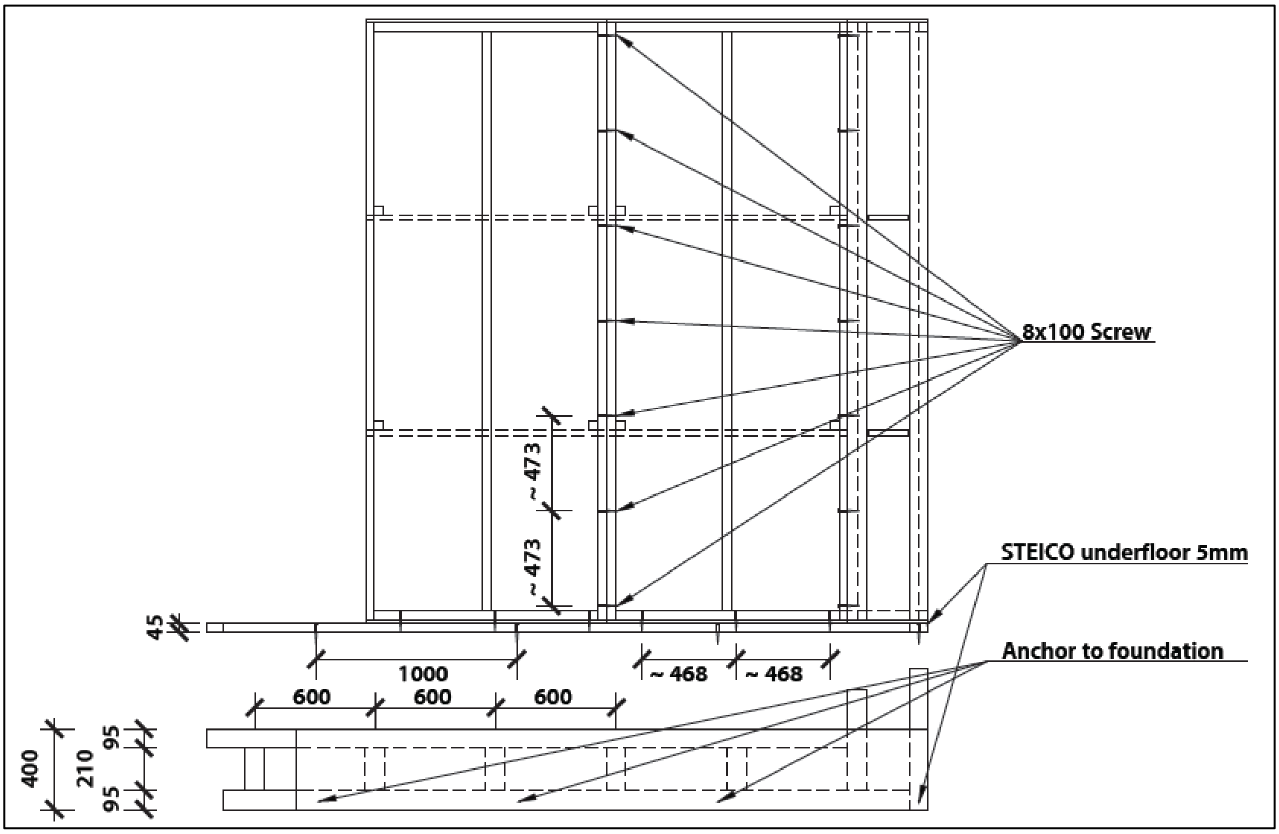


Figure A.7 Straw Solution Timber Frame Installation Details (Ecococon, 2015)

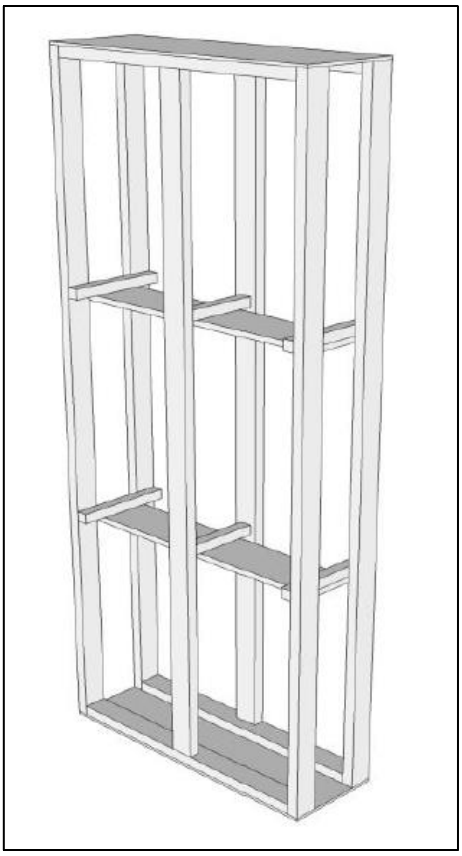


Figure A.8 Straw Solution Timber Frame Isometric View (SPSC, 2013)

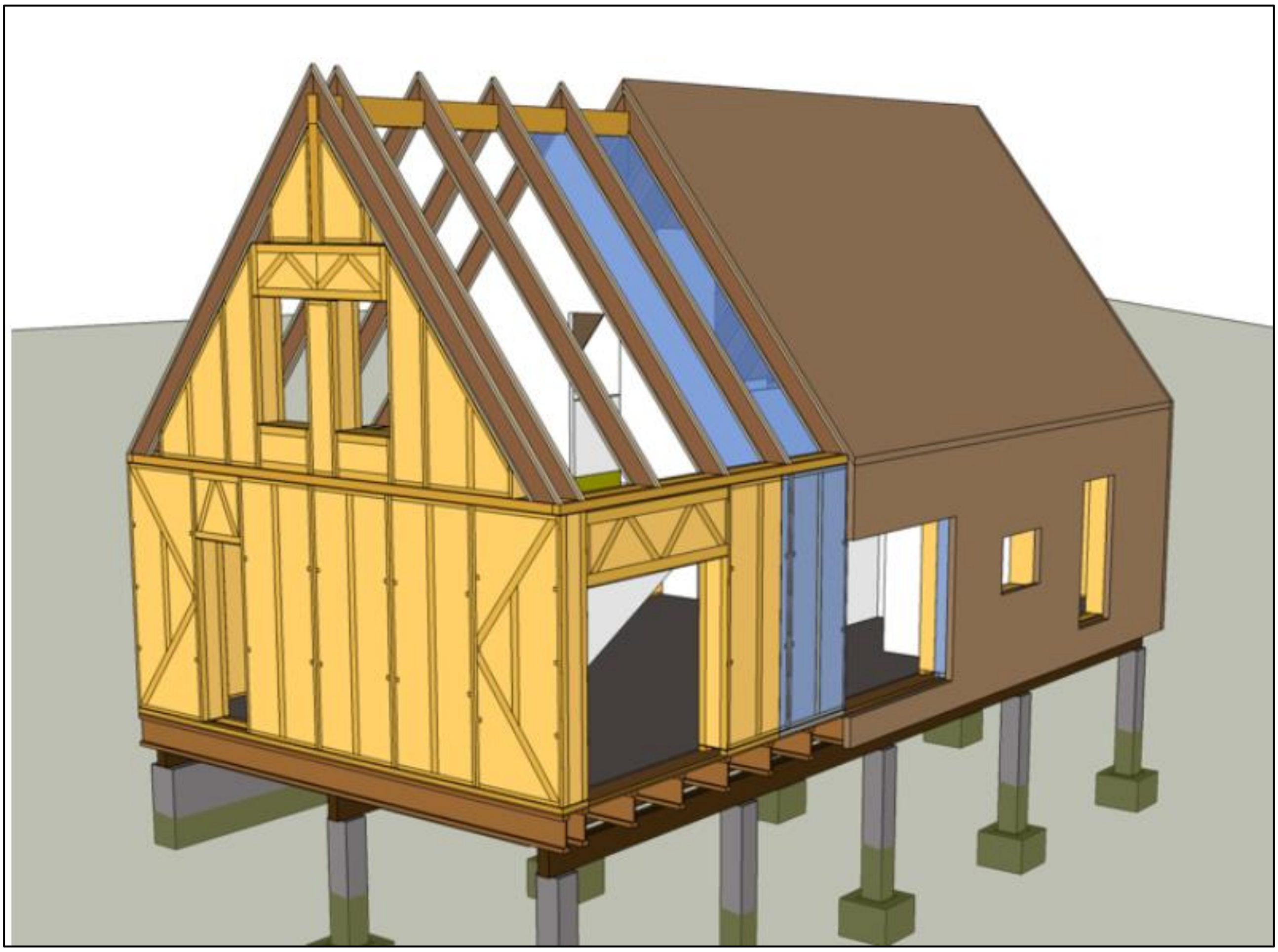


Figure A.9 Straw Solution Isometric View (Ecococon, 2015)

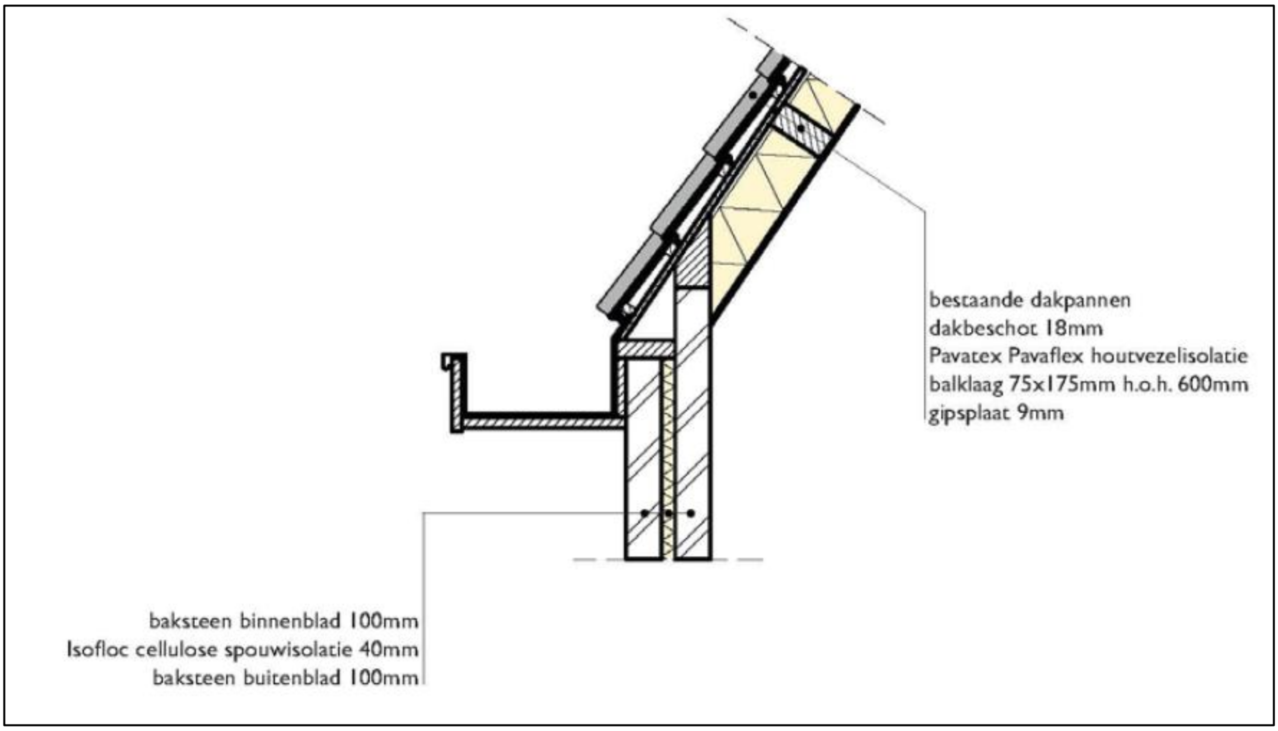


Figure A.10 Brick Solution Cavity Wall Cross Section Detail (Haagen, 2015)

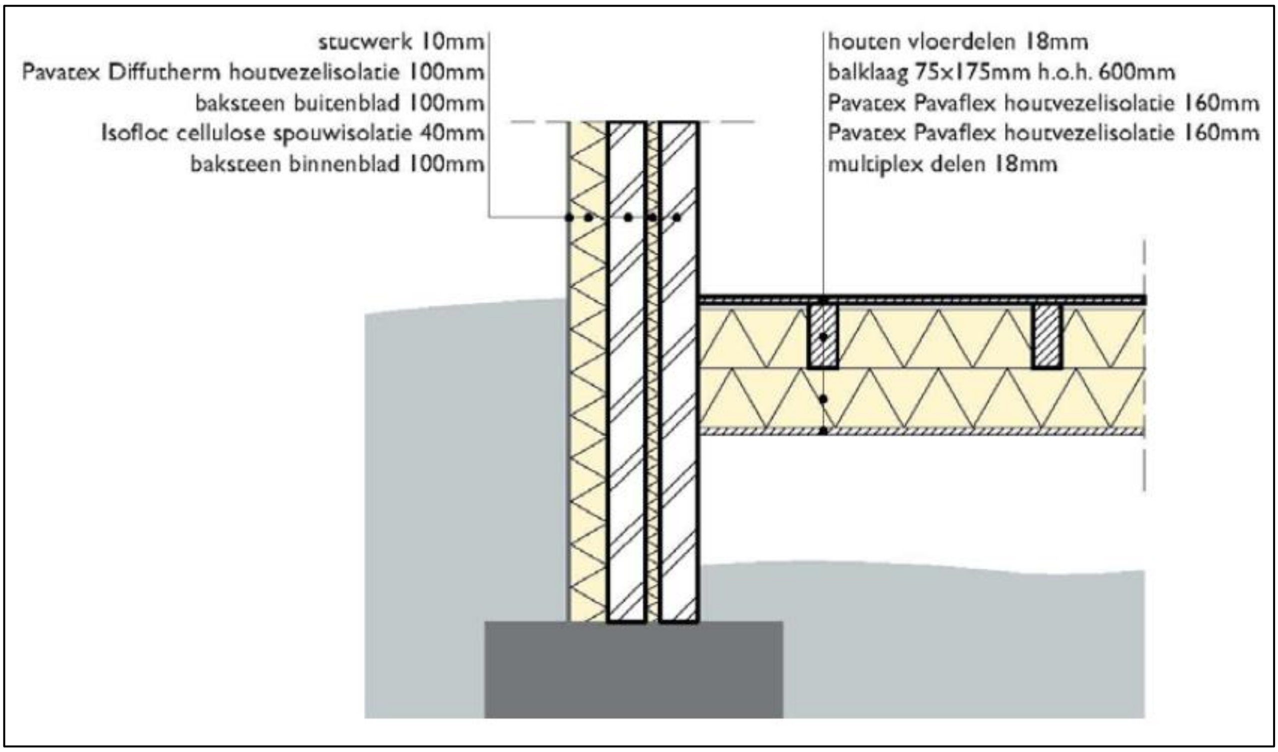


Figure A.11 Brick Solution Exterior Insulation Variation 1 Cross Section Detail (Haagen, 2015)

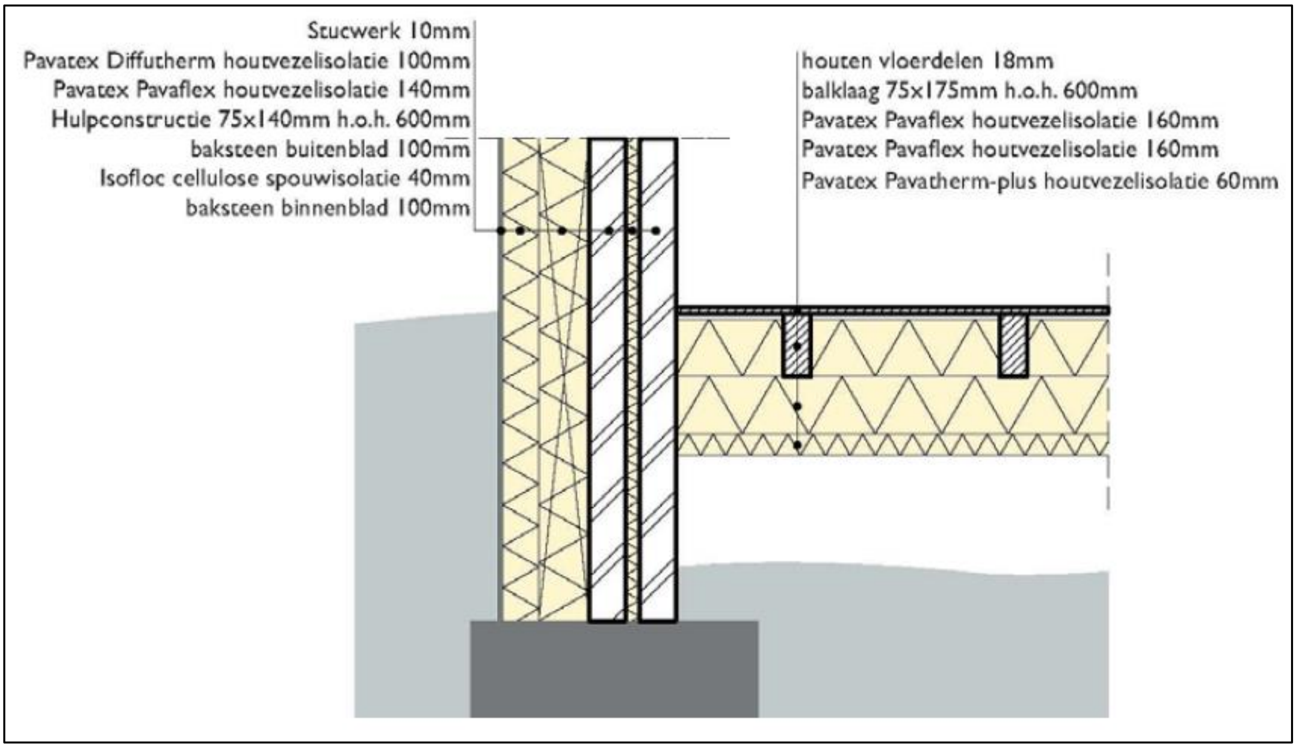


Figure A.12 Brick Solution Exterior Insulation Variation 2 Cross Section Detail (Haagen, 2015)

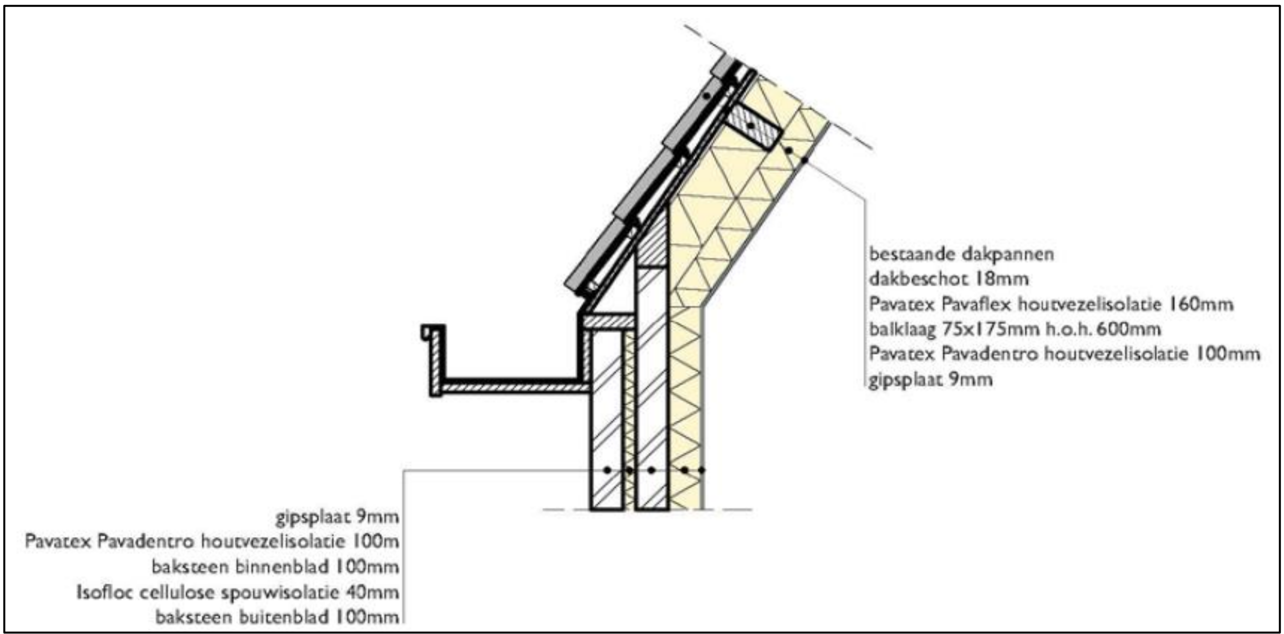


Figure A.13 Brick Solution Interior Insulation Variation 1 Cross Section Detail (Haagen, 2015)

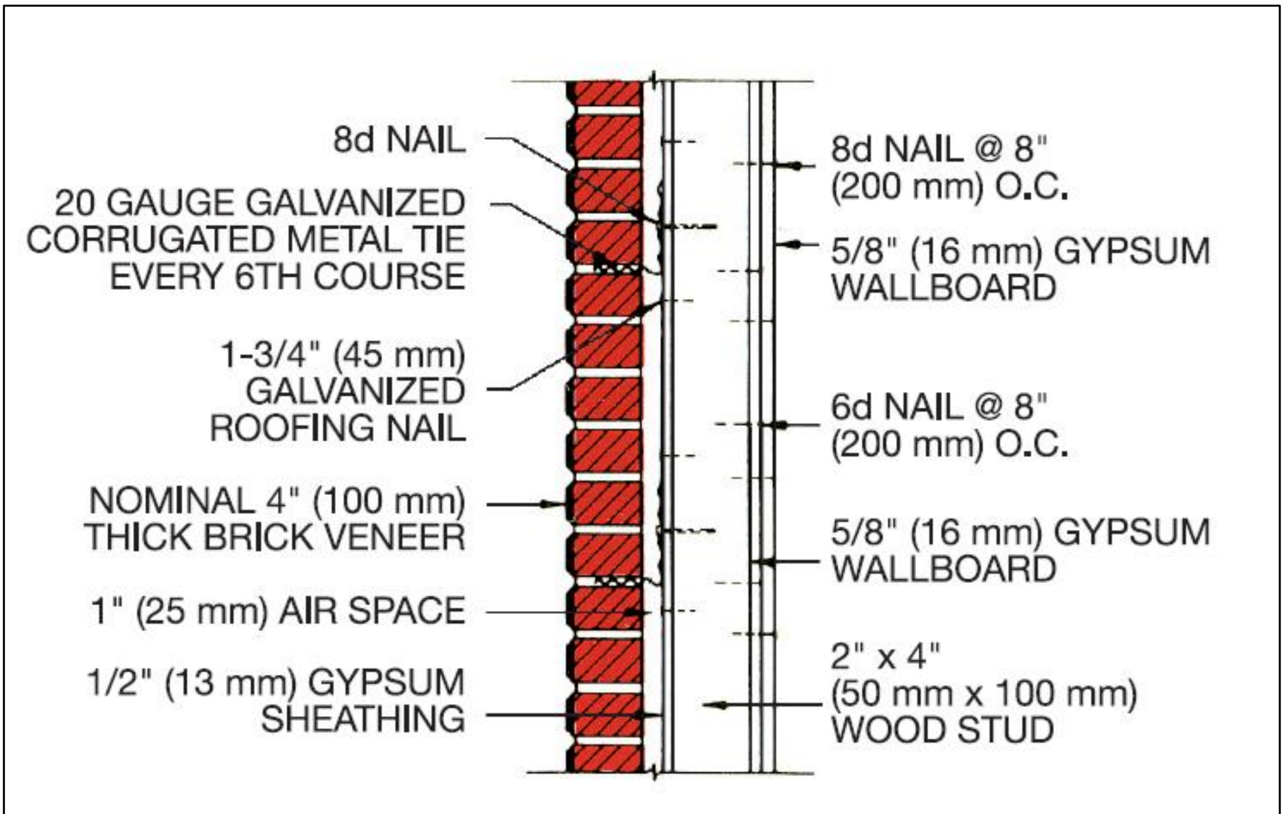


Figure A.14 Brick Solution Veneer Cross Section Detail (Endicott, 2015)

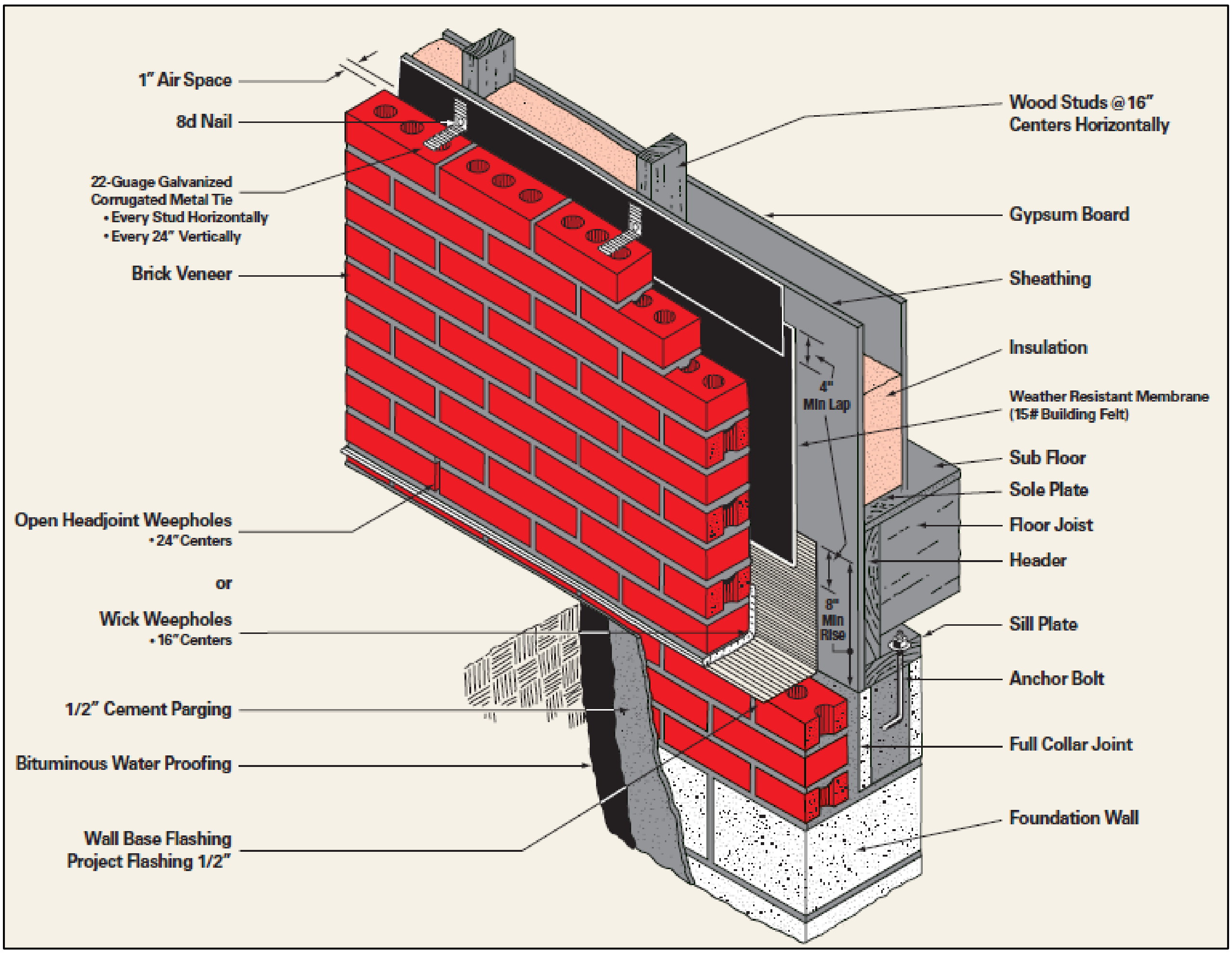


Figure A.15 Brick Solution Veneer Isometric Detail (Endicott, 2015)